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Orbiter / External Tank (ET) Mate Operations Final Report

Presented to:
United Space Alliance
Industrial Engineering and Human Factors

ISyE Senior Design Project

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This document has been proofed and
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EXECUTIVE SUMMARY

United Space Alliance (USA) has recognized that the S0004 Orbiter / External Tank (ET) Mate Operations process contains extreme variations in processing times for individual assemblies. As a result, more consistent processing times are needed, as well as cycle time reductions. The Georgia Institute of Technology (GIT) Senior Design team perform a thorough review of all the actual work, support, and procedures used to accomplish S0004 operations. The primary objectives were to develop a flexible and scalable model that will help to:

- Standardize day-to-day S0004 Operations
- Assist Resource Management in making operational support decisions with regards to staffing of skilled technicians
- Provide scheduling and resource allocation that consider process variables (i.e. day of week process starts, over-time availability)

The project work includes a network flow model and simulation model that satisfy the following objectives:

- Integrate with current USA settings and standards
- Explore several existing processes currently used to support operational and business decisions
- Develop procedures that will help determine "best course of action" and allow management to access information on a per user basis
- Confirm integrated scheduling processes based on collected data
- Analyze resource balancing
- Investigate a development of a S0004 critical path recovery plan

The benefits associated with the development of these models are as follows:

- Operational costs should be reduced by:
  - Locating and managing process bottle necks
  - Increasing throughput
  - Minimizing resource idle time
  - Identifying ideal scheduling options by exploring multiple "what if " scenarios
- It will be easier to make informed decisions regarding business or technical processes by:
  - Discovering the interaction between process
  - Evaluating the performance of current and future complex systems
  - Exploring alternative methods without disrupting the current system
  - Providing additional Next Step recommendations for improvement

Recommendations

Because of several incomplete data sets, results are inconclusive. Once data is collected, it is recommended that resources are added and allocated to the S0004 process based on bottlenecks in the LP and simulation models.

In addition, the simulation model will output the most efficient process flow based on resource availability and scenario analyses.

USA
United Space Alliance

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ORGANIZATION BACKGROUND

Organization: United Space Alliance

Location: Kennedy Space Center, Florida
8550 Astronaut Boulevard, USK-580
Cape Canaveral, FL 32920

Contact: Pat Floyd - Industrial Engineering & Human Factors Department Lead

Phone: (321) 861-6671

Headquartered in Houston, Texas, United Space Alliance (USA) is one of the world's leading space operations companies. Established in 1996 as a Limited Liability Company (LLC), USA is equally owned by The Boeing Company and Lockheed Martin Corporation and employs people in Texas, Florida, Alabama, California and Washington, D.C.

USA manages and conducts space operations work involving the operation and maintenance of multi-purpose space systems, including systems associated with NASA's human space flight program, Space Shuttle applications beyond those of NASA, and other reusable launch and orbital systems.

As the prime contractor for NASA's Space Shuttle Program, USA is responsible for the day-to-day operation and management of the U.S. Space Shuttle fleet and brings a broad range of expertise to the job, including:

- Mission Design and Planning
- Flight Operations
- Software development and Integration
- Payload Integration
- Integrated Logistics
- Astronaut and Flight Controller Training
- Vehicle Processing, Launch, and Recovery

USA and the Space Shuttle Program

USA has maintained safety and reliability as top priorities while successfully reducing the overall costs of operating the Space Shuttle fleet. Mission objectives – including preparation for flight, on-time launches and safe landings – are consistently met under USA's management. USA employees in Florida perform end-to-end ground operations in support of America's Space Shuttle fleet, including processing, logistics, launch, landing, recovery and turnaround operations, while Texas employees perform mission planning, astronaut and flight controller training, software development and verification, and mission operations from launch through landing.

USA's first and foremost goal is the safe and reliable management of the Space Shuttle fleet. While continually ensuring that the primary goal is met, USA is also involved in the operations of the International Space Station. As the only company in the world with extensive experience in the processing, maintenance, and operation of a reusable launch vehicle, USA will be offering its expertise to NASA.

USA Core Competencies

The SFOC includes responsibility for the Orbiters, Flight & Ground Operations, and Logistics:

At the Johnson Space Center (JSC) in Texas, USA performs:

- Flight Operations
- Astronaut & Flight Controller Training
- Space Shuttle Flight Simulator Operations
- Mission Control Center Management and Operations
- Mission Planning, Flight Design and Analysis
- Space Station Operations and Utilization
- Flight Software Development
- Flight Crew Equipment

At the Kennedy Space Center (KSC) in Florida, USA is responsible for Ground Operations:

- Vehicle Modification, Testing, Checkout and Launch Operations
- Support U.S. and Trans-Atlantic Emergency Landing Sites
- Ocean Retrieval of Solid Rocket Boosters
- Space Shuttle Logistics Depot - manufacture, repair and procurement of Shuttle hardware and ground support equipment.

INTRODUCTION

Actual processing time for Orbiter / ET Mate operations varies greatly. Management would like to have a more consistent processing time and cycle time reduction. In addition, multiple "what if" scenarios have been explored in order to identify the best options for process changes without disrupting the current system. Currently there is no real-life data being recorded and stored in a database.

Essentially, management wants a validity and higher user confidence of the integrated schedule. Management wants to reduce cycle time, cut operating cost, identify and manage bottlenecks, improve resource utilization, increase throughput, determine equipment idle time, and justify equipment needs. Resource Management has requested assistance and standardization in making real-time operational support decisions better informed with regards to business requirements. A tool has been developed to assist in determining real-time best course of actions and developing recovery plans.

PROBLEM STATEMENT

United Space Alliance (USA) is concerned that the S0004 Orbiter / External Tank (ET) Mate Operations process containing extreme variations in processing times for individual assemblies. USA is interested in stabilizing the S0004 process while reducing cycle times, matching critical resources to operations, and enhancing scheduling capabilities.

APPROACH

The S0004 process was analyzed from the start of Orbiter operations in the Vehicle Assembly Building (VAB) to Orbiter and ET mating processes atop the Mobile Launch Platform (MLP).

A network flow model represents the S0004 process as it currently stands. The model identifies bottlenecks and helps to validate a simulation tool for evaluating process operations. A linear program was developed to generate optimal resource allocations.

Once the network flow model and linear program were constructed and analyzed, a simulation tool was created to help manage bottlenecks, validate scheduling, and match resources to the operations.

As a final consideration, a scenario analysis was performed and integrated into the simulation software to test different parameter combinations and enhance decision-making capabilities. A suggested project recommendation is being provided to USA representatives to support a more efficient and beneficial S0004 process.

DELIVERABLES

The team has provided the United Space Alliance a scheduling and resource allocation model that will:

- Explore several existing processes used currently to support operational and business decisions
- Provide validity to the integrated scheduling process
- Determine optimal resource allocation
- Help to determine a best course of action

** Note: Deliverables are pending complete data collection.

DATA COLLECTION

Data needed to complete this project include:

- Steps involved with the S0004 process
- Cycle times of operations given in triangular distribution [minimum, most likely, maximum]
- Resources needed / available (i.e. equipment, technicians, engineers)
- Equipment resources and capacity rates
- Critical points and issues associated with the S0004 process
- Human resource labor required and capabilities (i.e. hours of work)
- Vehicle Assembly Building floor plan.

Network Flow Model

Figure 1 is a representation of the network flow model of the S0004 process. Each box represents a major subtask. The network flow model gives an idea of the size and scope of the S0004 process. The critical path is shown in red. Appendix A shows a more detailed network flow model.

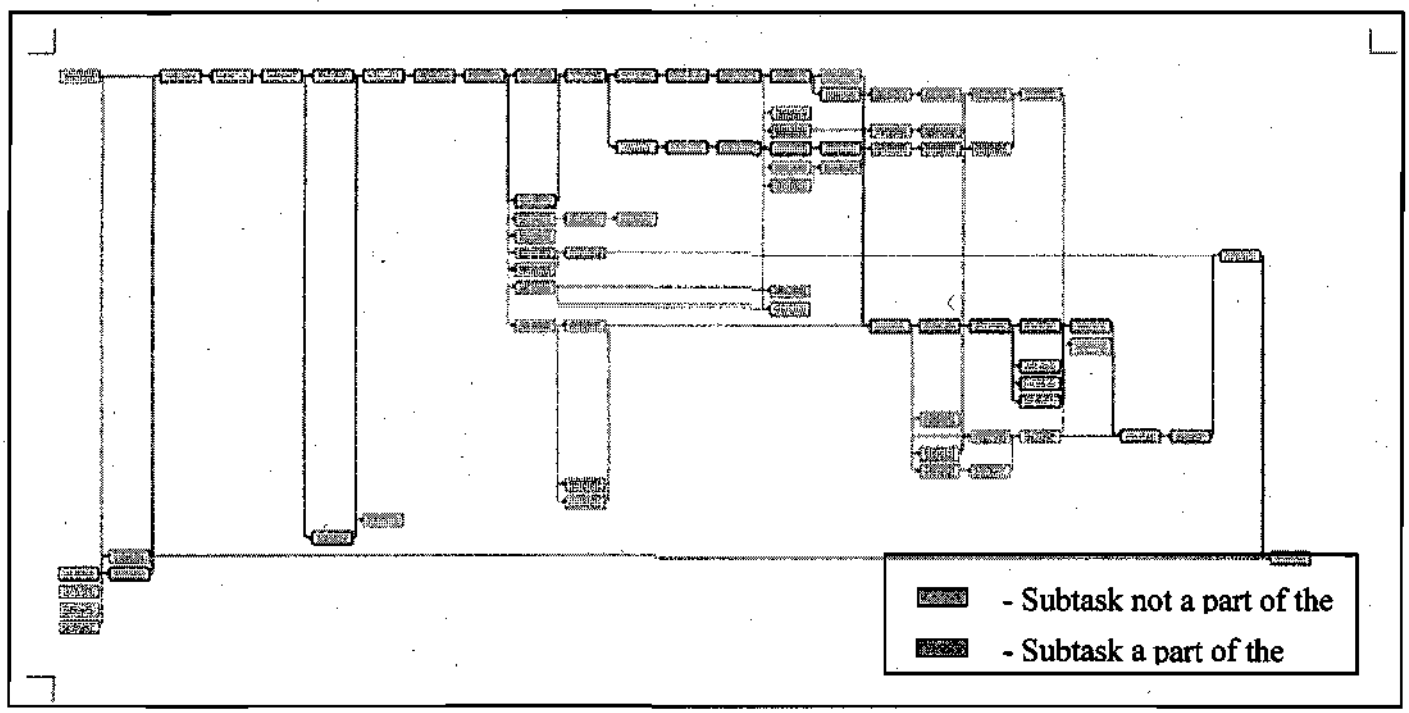
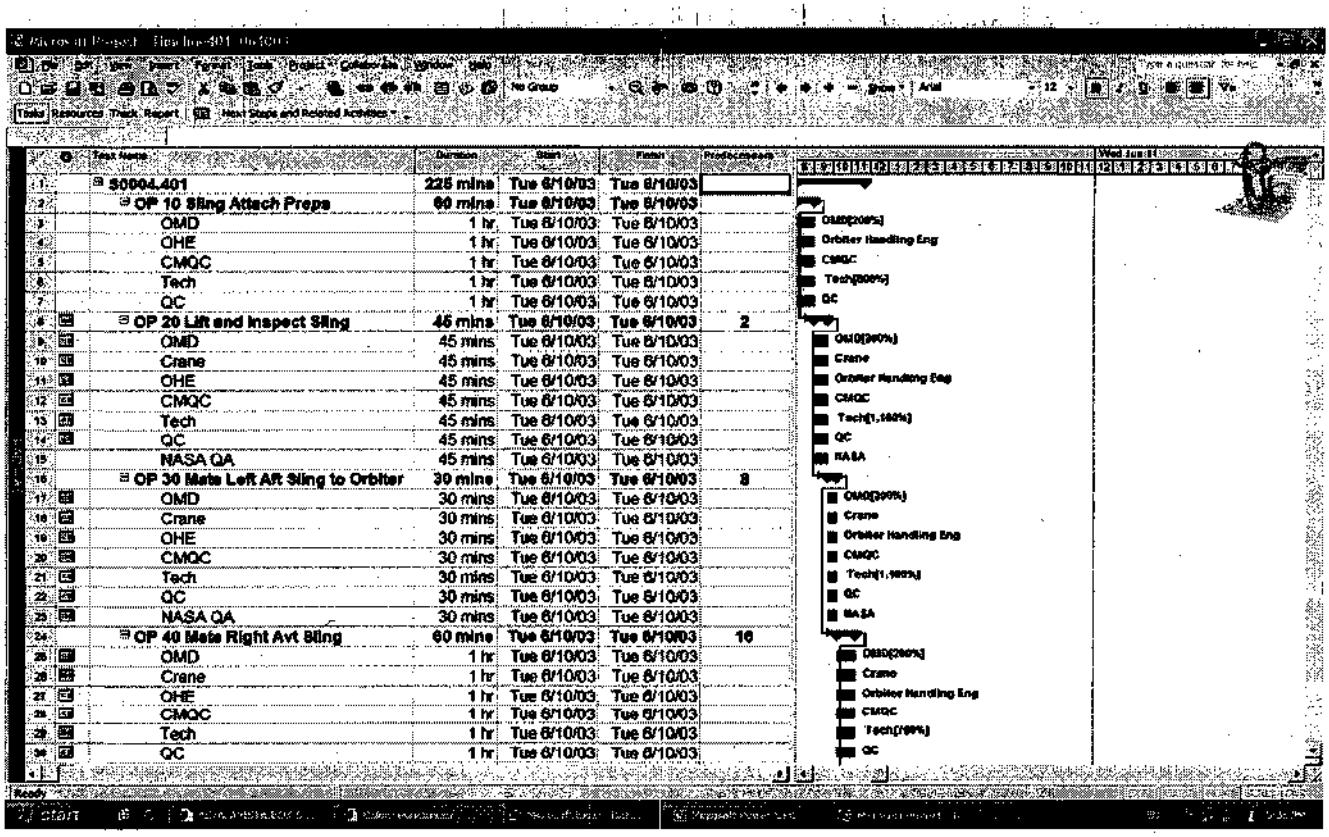


Figure 1: Network Flow Model of S0004 Process

Microsoft Project ™

Microsoft Project was chosen for use as a Scheduling / Planning Tool and for PERT analysis. It can be used for guided planning and management of tasks and resources to help set up projects and report project information; track and evaluate plans to help create schedules, estimate costs, track progress, and assign resources; and evaluate changes.



	Task Name	Duration	Start	Finish	Predecessors
1	S0004.401	225 mins	Tue 6/10/03	Tue 6/10/03	
2	OP 10 Sling Attach Preps	60 mins	Tue 6/10/03	Tue 6/10/03	
3	OMD	1 hr	Tue 6/10/03	Tue 6/10/03	
4	OHE	1 hr	Tue 6/10/03	Tue 6/10/03	
5	CMQC	1 hr	Tue 6/10/03	Tue 6/10/03	
6	Tech	1 hr	Tue 6/10/03	Tue 6/10/03	
7	QC	1 hr	Tue 6/10/03	Tue 6/10/03	
8	OP 20 Lift and Inspect Sling	45 mins	Tue 6/10/03	Tue 6/10/03	2
9	OMD	45 mins	Tue 6/10/03	Tue 6/10/03	
10	Crane	45 mins	Tue 6/10/03	Tue 6/10/03	
11	OHE	45 mins	Tue 6/10/03	Tue 6/10/03	
12	CMQC	45 mins	Tue 6/10/03	Tue 6/10/03	
13	Tech	45 mins	Tue 6/10/03	Tue 6/10/03	
14	QC	45 mins	Tue 6/10/03	Tue 6/10/03	
15	NASA QA	45 mins	Tue 6/10/03	Tue 6/10/03	
16	OP 30 Mate Left Aft Sling to Orbiter	30 mins	Tue 6/10/03	Tue 6/10/03	8
17	OMD	30 mins	Tue 6/10/03	Tue 6/10/03	
18	Crane	30 mins	Tue 6/10/03	Tue 6/10/03	
19	OHE	30 mins	Tue 6/10/03	Tue 6/10/03	
20	CMQC	30 mins	Tue 6/10/03	Tue 6/10/03	
21	Tech	30 mins	Tue 6/10/03	Tue 6/10/03	
22	QC	30 mins	Tue 6/10/03	Tue 6/10/03	
23	NASA QA	30 mins	Tue 6/10/03	Tue 6/10/03	
24	OP 40 Mate Right Avt Sling	60 mins	Tue 6/10/03	Tue 6/10/03	16
25	OMD	1 hr	Tue 6/10/03	Tue 6/10/03	
26	Crane	1 hr	Tue 6/10/03	Tue 6/10/03	
27	OHE	1 hr	Tue 6/10/03	Tue 6/10/03	
28	CMQC	1 hr	Tue 6/10/03	Tue 6/10/03	
29	Tech	1 hr	Tue 6/10/03	Tue 6/10/03	
30	QC	1 hr	Tue 6/10/03	Tue 6/10/03	

Figure 2 : Microsoft Project

Figure 2 is a snapshot of the program. The tasks are all listed with their durations. The bolded lines are major tasks and subtasks are tabbed and listed underneath. For example, S0004.401 is a major subtask and its subtasks are Operations 10, 20, and so forth. The lists under the Operations such as "OMD, OHE, CMQC, Tech, QC" represent the different types of resources needed for that particular operation. The bar chart on the far right shows the length of times those resources are needed and at what point in the operation they are needed. The percentages, for example, 200% after OMD means there are two OMD's needed for the operation at that particular time. The numbers in the Predecessors column represent the line item if the task that precedes that task. The complete Microsoft Project file is in Appendix B.

Task Durations

Because there is no existing historical data for the S0004 process, it was decided that a triangular distribution would be used to evaluate and analyze the process. The minimum, most likely, and maximum durations known were collected and the data was put in a spreadsheet (shown in Appendix C).

Resources

Figure 3 is a spreadsheet showing resources required for the S0004 process. It identifies the number of resources available to work during all three shifts. The resource names used in the Microsoft Project file and the resource names given in the Excel sheet by USA differed. Therefore, a spreadsheet was made in order to identify the resources and their different names. For example, the second line in Figure 3 shows that "Crane" and "Platform Operators" are the same as "Crane Crew" in the resource list that was provided.

RESOURCES		SHIFTS		
from Project	from given list	1st Shift	2nd Shift	3rd Shift
CMQC	CMQC	5	4	2
Crane Platform Operators	Crane Crew	12	12	6
ETM	ETM	3	0	0
Flight Crew Systems QC	Flight Crew Systems QC	1	1	0
Flight Crew Systems Tech	Flight Crew Systems Tech	5	4	0
Heavy Equipment	Heavy Equipment	8	6	0
High Crew	HIGH CREW	4	4	0
Launch accessories ENG.	LAA	2	0	0
MLP Tech	MLP Tech	23	15	
MPS	MPS	2	1	0
NASA ETM	NASA ETM	3	0	0
NASA LAA	NASA LAA	2	0	0
NASA OEL Eng.	NASA OEL	2	0	0
NASA NASA QA	NASA QA	10	6	2
NDE QE	NDE QE	2	0	0
NDE TECH	NDE Tech	4	4	0
OEL Eng.	OEL	2	2	0
OHE	OHE	6	0	0
OMD	OMD	6	3	1
OPS	OPS	2	2	0
QC	Orbiter QC	12	8	1
1245 Operator 1245 TECH Cable Monitor Tech	Orbiter Tech	25	14	3
Pyro Eng.	PYRO	5	0	0
T ops QC	T Ops QC	10	10	6
T ops T ops Observer	T Ops Tech	18	17	15
Transporter crew	Transporter Crew	6	0	0
USA Safety	USA Safety	4	3	2

Figure 3 : Resources

LINEAR PROGRAMMING MODEL

Overview

The linear program (LP) is an essential aspect of the USA scheduling tool kit. It provides information that validates simulation results, provides a high level S0004 process flow run time, and produces a highly accurate scheduling sequence based on resources and precedence relationships. The LP allocates USA resources according to the precedence relationships in a feasible manner accounting for scenarios involving resource shortages and critical path mapping. Additionally, it provides a usable scheduling sequence based on time periods (specifically, completion times). From this information, the Georgia Tech Team will have sufficient data to compare to ProModel results.

Methodology

Linear programming is key in understanding how to fix the resource allocation problem that USA currently faces. Within the Linear Program (LP) formulation and solving, the GIT team will be able to assess variable considerations such as: resource constraints, matching of resources, precedence relationships, and identification of bottlenecks. Manpower accessibility and compensation time (overtime vs. straight time) are optimal for S0004 job initiation. The leveraging of all of these factors will produce a process that is superior to that in use today by USA.

The equation

$$\phi(x) = \sum_{t=EF_j}^{LF_j} t * xj_n$$

where

x = process time

j = task

will be used to solve the LP, focusing on the earliest start time to the latest finish time. X is a binary variable indicating if task j is being performed at a particular time. The first summation accounts for all resources and the second summation sums all time periods.

Upon completion of the LP, the GIT team will use simulation to view the performance of the linear program. Within this simulation, various constraints will be tested to manage identified bottlenecks, scheduling, and resource operational issues. This testing will provide validity to the actual LP formulation. Simulation will be advantageous because the process is too complicated for LP or PERT analysis alone, scenarios can be tested in the simulation rather than in real-life (which could be disastrous).

Microsoft Project will be used as a scheduling / planning tool. It can be used for guided planning and management, tracking and evaluating plans, and evaluating changes. MS Project also has the ability to perform PERT analysis. Within PERT analysis the GIT team will be able to create schedules in addition to estimating cost and tracking progress.

Program Type

Type of LP: Resource Constrained Project Scheduling Model

This method focuses on a project that consists of activities (steps) that are linked by two kinds of restrictions, namely precedence and resource constraints. For each step, the duration, the resource requests, and the precedence relations with other steps are given. For each resource, the availability is given. All information on durations, precedence relations, and resource requests and availabilities are assumed to be deterministic and known in advance. The correct formulation of this model will only produce feasible solutions to the LP.

Note: this is an extremely difficult LP to solve and is characterized as an NP-hard problem (no optimal solutions can be determined with current technology)

Types of Constraints:

1. Objective Function (minimizes f(X) where f(X) will be process completion time)

2. Precedence
   a. Binary variables are used to denote that a step has been completed at a particular time period and done only once per step

   b. Multiple variables are used to establish that a successive step cannot begin until its predecessor is completed

3. Resource (earliest and latest finish times for a particular steps are needed to identify if there are enough resources available to meet resource requests)

Minimize $\sum_{t=EF_{J+1}}^{LF_{J+1}} t * x_{J+1,t}$ 1.1

$$\sum_{t=EF_j}^{LF_j} x_{jt} = 1, j \in J^+$$ 1.2

$$\sum_{t=EF_h}^{LF_h} t * x_{ht} \leq \sum_{t=EF_j}^{LF_j} (t - p_j) * x_{jt}, j \in J^+, h \in P_j$$ 1.3

$$\sum_{j=1}^{J} r_{jk} \sum_{b=\max\{t,EF_j\}}^{\min\{t+p_j-1,LF_j\}} x_{jb} \leq R_k^\rho, k \in K^\rho, t \in T$$ 1.4

$$x_{jt} \in \{0,1\}, j \in J^+, t \in T$$ 1.5

Resource Constrained Project Scheduling Problem (RCPSP)

The S0004 Process flow problem maps directly to what is commonly known as the resource-constrained project scheduling problem. This model is used when a process consists of activities (or jobs) that are linked by two primary restrictions, precedence and resource constraints. For steps, the following information was used:

- Duration times for each step considered in the process
- Resources requested for a particular step
- Precedence relations that a particular step has with other jobs or activities
- Availability of specific resources per time period.

All the aforementioned information is assumed to be deterministic and known in advance.

RCPSP Methodology

USA is interested in mapping the S0004 scheduling tool kit onto similar processes within the organization. Therefore, a detailed overview of the RCPSP is needed. To better understand the linear programming methodology for the S0004, consider a project (S0004) with J activities which are labeled j=1, ..., J. (S0004 consists of 113 steps = J)

The processing time, or duration time, of an activity j is denoted as d_j. The assumption here is that the planning horizon (overall time needed to complete the entire S0004 process) is divided into time intervals of equal duration called periods, and that the processing times d_j are given as discrete multiples of one period. This means that the S0004 process will be considered in terms of 15 minute intervals.

Here is an example of how the coding works in capturing the S0004 process. Note that the example's periods are in hours. Once a job has commenced, that activity may not be interrupted; therefore, preemption is not allowed. Additionally, each activity may have a predecessor. For example, one process cannot begin without the previous job being completed and freeing up some necessary resources needed for the later process. The precedence relations are given by sets of immediate predecessors P_j meaning that an

activity j cannot start unless each of its predecessors activity i is completed, ($i \in$ in P_j means that at some point in time, activity i is considered a predecessor to activity j).

Now, we will consider two additional activities j = 0 and j = J + 1 representing respectively the beginning and end of the project (dummy nodes). Activity 0 is assumed to be the unique source of the network while activity J + 1 is the unique sink. Both activities are "dummy" jobs in that their processing time is $d_0 = d_{J+1} = 0$. The set of all activities including the dummy jobs is denoted as $J+ = \{0, ..., J + 1\}$--- all steps considered in the entire S0004 process.

Aside from the source and sink activities (start and end), each activity consumes a certain number of resources. The resources are renewable because their full capacity is available in every period (after it has been used). Two examples of these resources would be manpower and machines, which are primary resources required in the S0004 process. An example of a nonrenewable resource would be raw materials.

The set of renewable resources is designated as K_p. For each resource, $k \in K_p$, the per-period-availability is assumed to be constant, known, and given by R^p_k. Activity j requires r_{jk} units of resource k in each period in its process. This means that the S0004 process has a certain number of resources (27) and for every resource the number and hours they are available to work is known. Additionally, a step needs a specific number of resources.

In addition, the parameters are assumed to be nonnegative and integer valued (duration times, earliest and latest finish times). It is also important to compute time windows for the activities. These time windows essentially provide information about start and finish times of an activity that allow completion of the whole project within some planning horizon.

For example, an upper bound T (usually the sum of the individual process times plus any additional slack) is needed on the project's makespan, and this can easily be computed as $T = \sum d_j$ (from j = 1 to J). The critical path of the entire process will always be defined as the lower bound. Assuming that the project starts at time 0, the earliest possible

starting time ES_j and the earliest finish time EF_j for each activity by utilizing forward recursion. Additionally, backward recursion is needed in order to compute the latest possible start time LS_j and the latest finish time LF_j for each activity. Thus, activity j must start with the time window $\{ES_j, ..., LS_j\}$ and finish within the time window $\{EF_j, ..., LF_j\}$. Starting each activity at its earliest start time leads to a precedence-feasible schedule, but it is not necessarily a resource-feasible schedule.

We define a binary variable x_{jt} for each activity $j \in J^*$ and each time interval $t \in T$ by denoting $x_{jt} = 1$ if activity j is finished at time t, and $x_{jt} = 0$ otherwise. This means that a binary variable "x" will be a 1 if an activity is completed at a particular instance in time and a 0 if it is not. The overall objective of the RCPSP is to find the minimal makespan, or in other words, to find a schedule which allows for the earliest possible end of the project. Obviously, the precedence and resource constraints may not be violated.

AMPL Software ™

The LP is comprised of thousands of variables and constraints. Therefore, a powerful linear programming software is required to solve the RCPSP. The Georgia Tech team chose AMPL as a suitable application to model the S0004 RCPSP.

AMPL is a computer language for describing production, distribution, blending, scheduling and many other kinds of problems known generally as large-scale optimization or mathematical programming. Additionally, it is a comprehensive and powerful algebraic modeling language for linear and nonlinear optimization problems, in discrete or continuous variables. The iterations processed from this application software provide the most feasible (not necessarily optimal) solution possible through current technology.

Developed at Bell Laboratories, AMPL allows the use of common notation and familiar concepts to formulate optimization models and examine solutions, while the computer manages communication with an appropriate solver. For the S0004 Problem, the most recent version of the CPLEX 8.1 solver was used.

A mathematical programming formulation for the RCPSP has three specific purposes:

1. Concrete and accurate problem definition
2. Usable formats can be easily inputted and updated using mathematical programming software
3. Feasible scheduling solutions can be quickly yielded

LP Methodology - Prototype

To best map the S0004 Process, a significantly smaller version of the actual process was developed and run. This process contained only 6 steps and 2 resources (with different availabilities). Figure 4 shows a snapshot of the process flow of the smaller program.

LP Methodology - Prototype

To best map the S0004 Process, a significantly smaller version of the actual process was developed and run. This process contained only 6 steps and 2 resources (with different availabilities). Figure 4 shows a snapshot of the process flow of the smaller program.

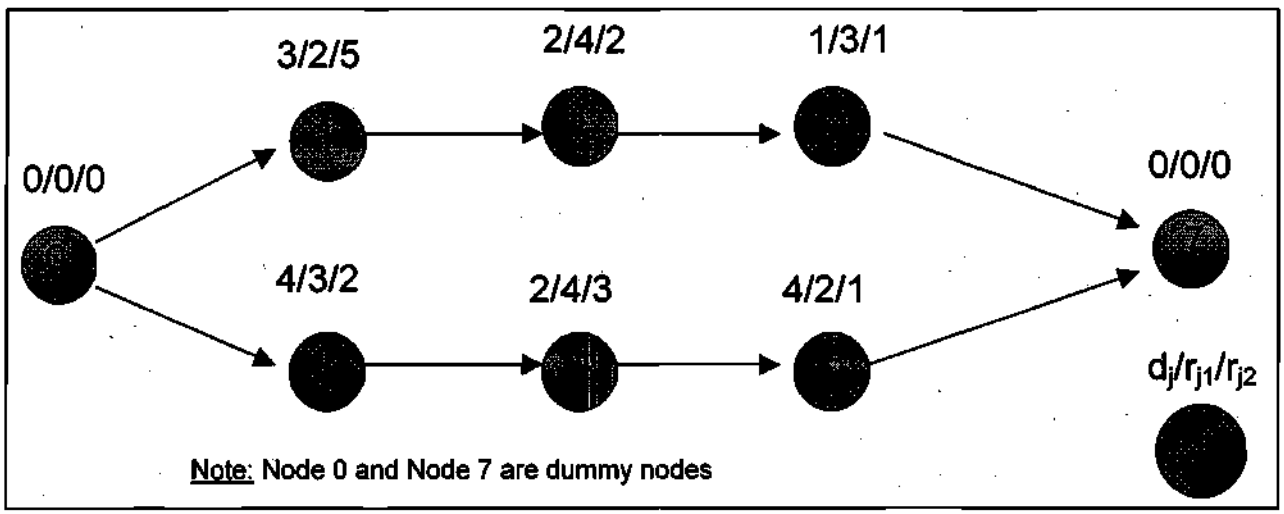


Figure 4 : Prototype Process Flow

As described above, the nodes 0 and 7 are dummy nodes which allow for delays in process start and ends, and J is denoted as 6. The process flow shows the precedence relationships. For instance, activity 3 cannot happen until activity 1 is completed. The three numbers listed above each activity signifies the duration time and resources needed for each activity. For example, in process 3, there is a duration time of 2, and it needs 4 resources from resource one and 2 resources from resource 2.

Step, j	Successor	Duration	R_1=4 r_1	R_2=5 r_2
0	1 and 2	0	0	0
1	3	3	2	5
2	4	4	3	2
3	5	2	4	2
4	6	2	4	3
5	7	1	3	1
6	7	4	2	1
7	empty	0	0	0

Figure 5 : Information Flow Diagram

The information flow diagram in Figure 5 lists the steps, the successors, the duration times needed for each resources 1 and resources 2. The duration times are given in hours and there are 4 hours of resource 1 available and 5 hours of resource 2 available. For example, step 1 takes 3 hours and its successor is step 3. It utilizes 2 hours of resource 1 and 2 hours of resource 2.

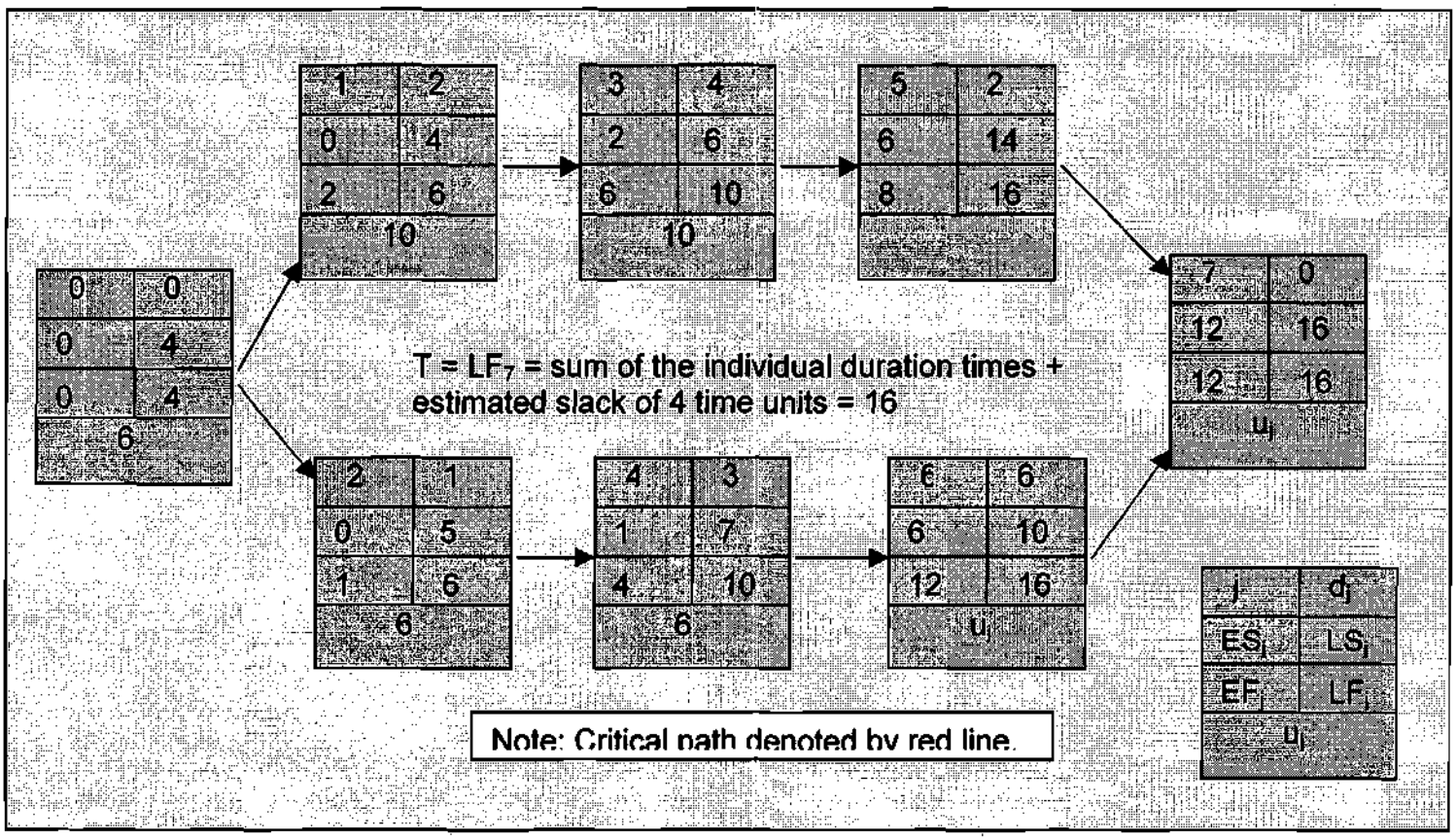


Figure 6 : Start / Finish Time Chart

Figure 6 shows a diagram of our simple prototype of seven steps. Steps 0 and 7 are the dummy nodes, and the critical path in the diagram is designated by the red line. The seven boxes for each step j indicate the step number j, the duration time d_j, the earliest start time ES_j, the latest start time LS_j, the earliest finish time EF_j, the latest finish time LF_j, and u_j.

Time windows were created for each step and the latest finish time "T" for the entire process. The Latest finish time was found to be 16 hours with additional slack placed at the end of the process. (slack can be added onto T to account for unexpected occurrences).

Project Schedule based on LP Solution

- Binary Variables depict completion times
- Limited Resources increase processing time (i.e. step 3 must wait on step 4 to complete
- RCSP cannot give optimal solutions (only feasible approximations)

CPLEX 8.0.0 shows that the optimal integer solution has objective function value 14, which equals the process make span (total completion time). For complete coding and results see Appendix D.

LP Methodology – Prototype Testing

The following output was gathered after LP formulation using AMPL:

The program displays a scheduling matrix that shows when each activity will be completed based on resources available and precedence relations (See Appendix D). The vertical column represents the total number of hours allowed to complete the entire process (16). The horizontal columns denote each activity (0 through 7). The binary variable x illustrates if a process was completed during a specific time period. For instance, activity 3 was completed at time 8. Because it has a duration time of 2 hours, activity 3 must have started in time period 6.

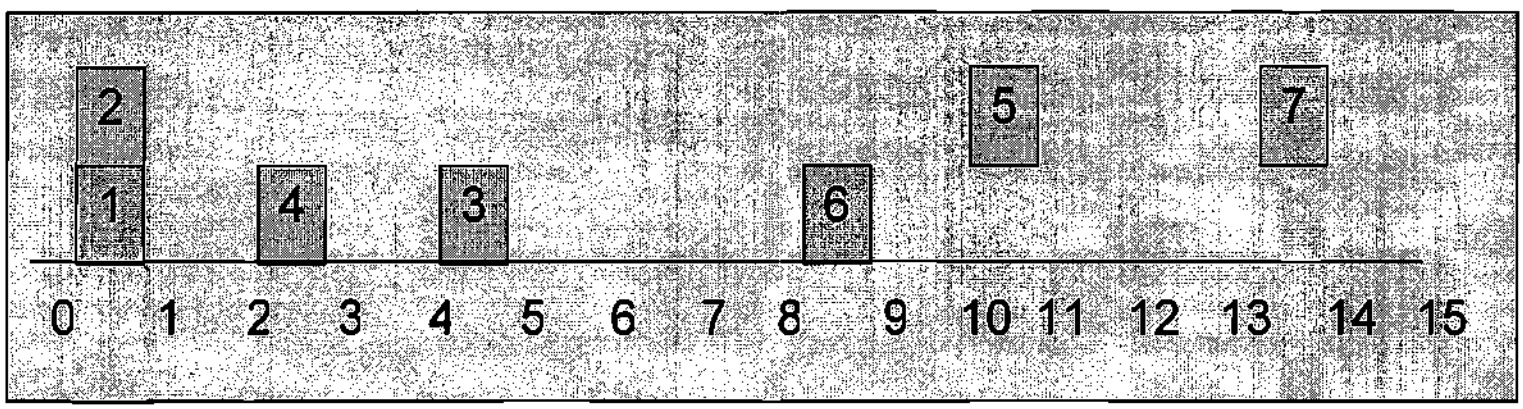


Figure 7 : Schedule

Figure 7 displays the binary variables in a usable project schedule. Precedence and resource availability force the program to schedule out of numerical order and thus provide a feasible solution (most optimal solution to date based on available technology).

S0004 Results

Using an advanced model of the AMPL software, the S0004 run-time results equal 72.45 hours. Complete coding and results from the LP are in Appendix E.
Appendix F provides a complete schedule with start, stop, and duration times. This schedule is based on the most efficient process flow.
The Gantt Chart in Appendix G is a pictorial representation of the schedule shown in Appendix F.

Future Considerations

Because of incomplete resource data sets, the LP model only represents the least amount of time needed to complete the S0004 process. Additionally, the program does not contain shift differences. To reconfigure the LP, an additional line of coding is needed to input shifts and the remaining resource availability data is needed to ensure the most accurate representation of the S0004 process. This requires minimal coding and time. This process will help to facilitate bottleneck locations based on extreme variations in start, stop, and duration times of any particular step.

SIMULATION MODEL

Overview

Simulation Modeling was used to imitate the S0004 process. Simulation is advantageous because it allows:

- The study of a complicated process through simulation in order to fully study it using analytical or numerical treatment
- Use of the model as a basis for experimental studies of the systems
- Use of the model in order to check results and give credibility to conclusions obtained by methods other than simulation.

In addition to the advantages listed above, simulation allows for scenario analysis without disrupting the real-world system. This, of course, is important because it helps to prevent disastrous situations, save time, and save money.

Unlike the LP model, the simulation model takes resource availability according to shifts into consideration.

ProModel is the simulating software requested for use by USA.

Programming

Locations, entities, paths, resources, and graphics were created first. Once they were created, the processing logic was coded. Data from the Microsoft Project file was used to input resources and task durations. In order to follow precedence relationships, ProModel's logic was manipulated in certain ways.

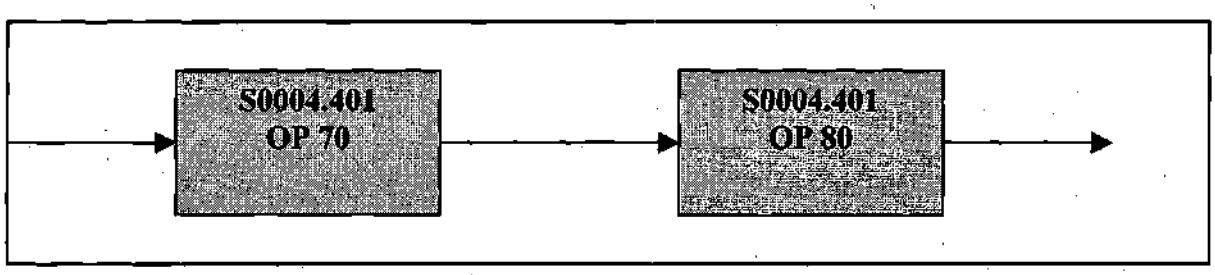


Figure 8 : Precedence Relationship A

Figure 8 shows a part of the S0004 network flow. In this case, S0004.401 OP 70 precedes S0004.401 OP 80.

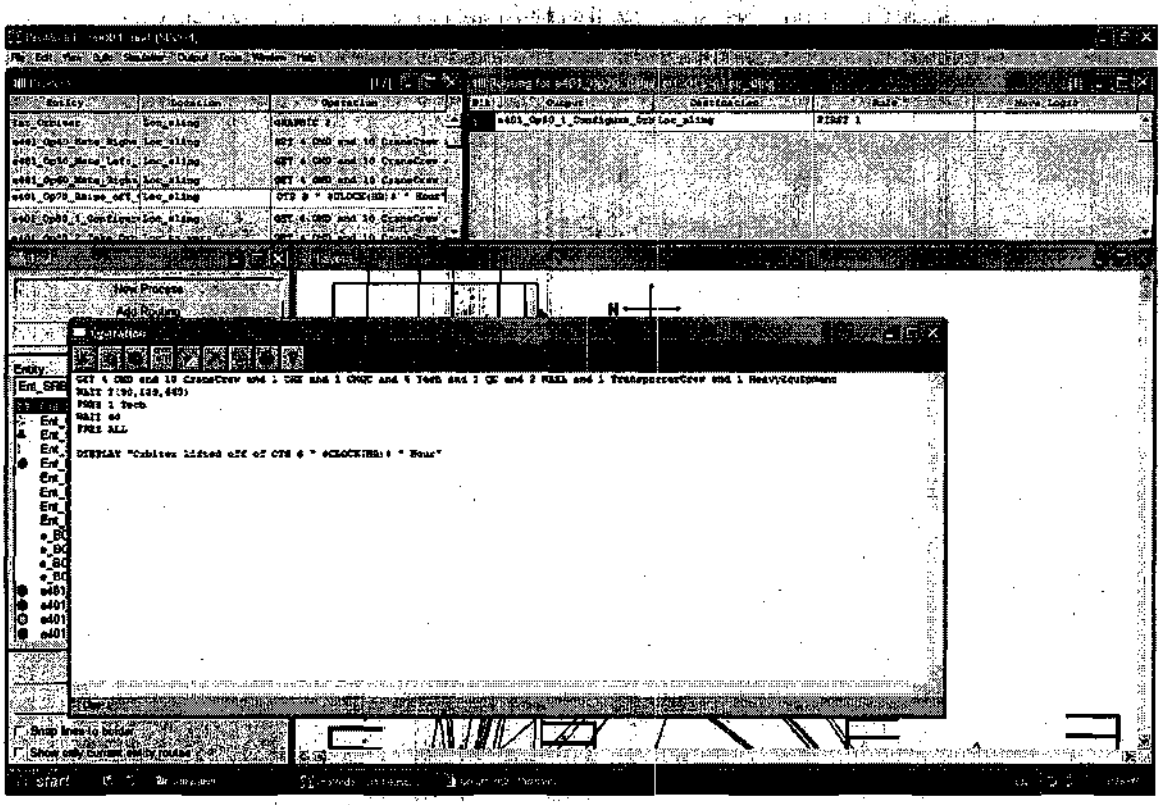


Figure 9 : ProModel (Processing Logic)

Figure 9 shows ProModel's Build Processing screen. The processing logic for S0004.401 OP 70 is shown. The entity e401_OP70_Raise_off_OTS is in the location named Loc_Sling, and its operation logic is shown at the bottom in the "Operation" window. First, all resources needed for the task are captured. This logic reflects how resources are actually called for tasks during the S0004 process. All resources needed for the task are called at the start of the task. Although a resource may not be needed until some time in the middle of the task, all resources needed for the entire task are called at the start in order to reduce wait time for resources during the task, which can be critical to tasks. For example, a QC is not needed until 1 hour after the start of the task and waits until he is needed an hour later. Once he is done with his responsibilities, he is freed and becomes available to work another task. The Operation window shows that S0004.401 OP 70 needs the following resources: 4 OMD, 6 CraneCrew, 1 Tech, 6 Tops, 1 QC, 1 NASA, 1 OHE, 1 CMQC, 1 ETM, and 1 NASA ETM. 'WAIT T(180,240,300)' tells the simulation to

run a duration of time. The 'T' represents the triangular distribution. The numbers represent the minimum, most likely, and maximum durations, respectively. Next, 1 Tech resource is freed. The tech is freed at this point because he is no longer needed for this task. The simulation runs for another duration of time and frees all resources. The DISPLAY function displays the completion time of a particular milestone. In this case, it is the time in which the Orbiter is lifted off the OTS (Orbiter Transporting System). The task exits the system and outputs the next task, e401_OP80. This is shown in the Routing window. The output creates the entity and the processing logic moves on to execute its processing logic.

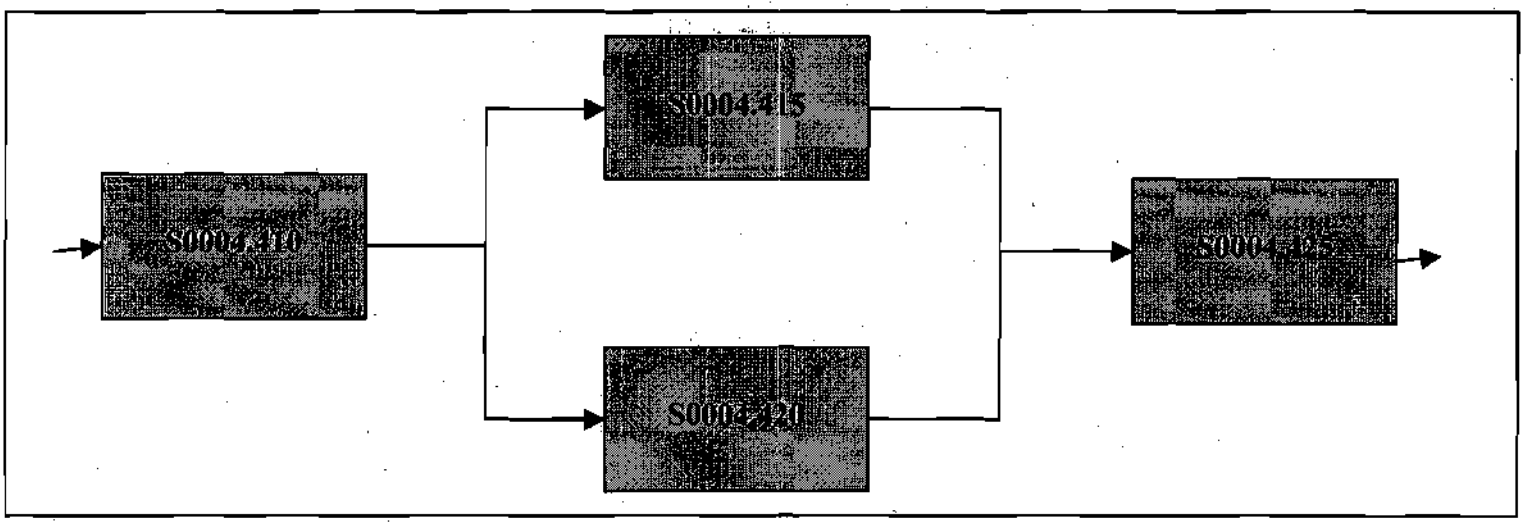


Figure 10 : Precedence Relationship B

Figure 10 represents the process flow where the completion of S0004.410 starts tasks S0004.415 and S0004.420, which are worked in parallel. S0004.425 starts at the completion of both S0004.415 and S0004.420.

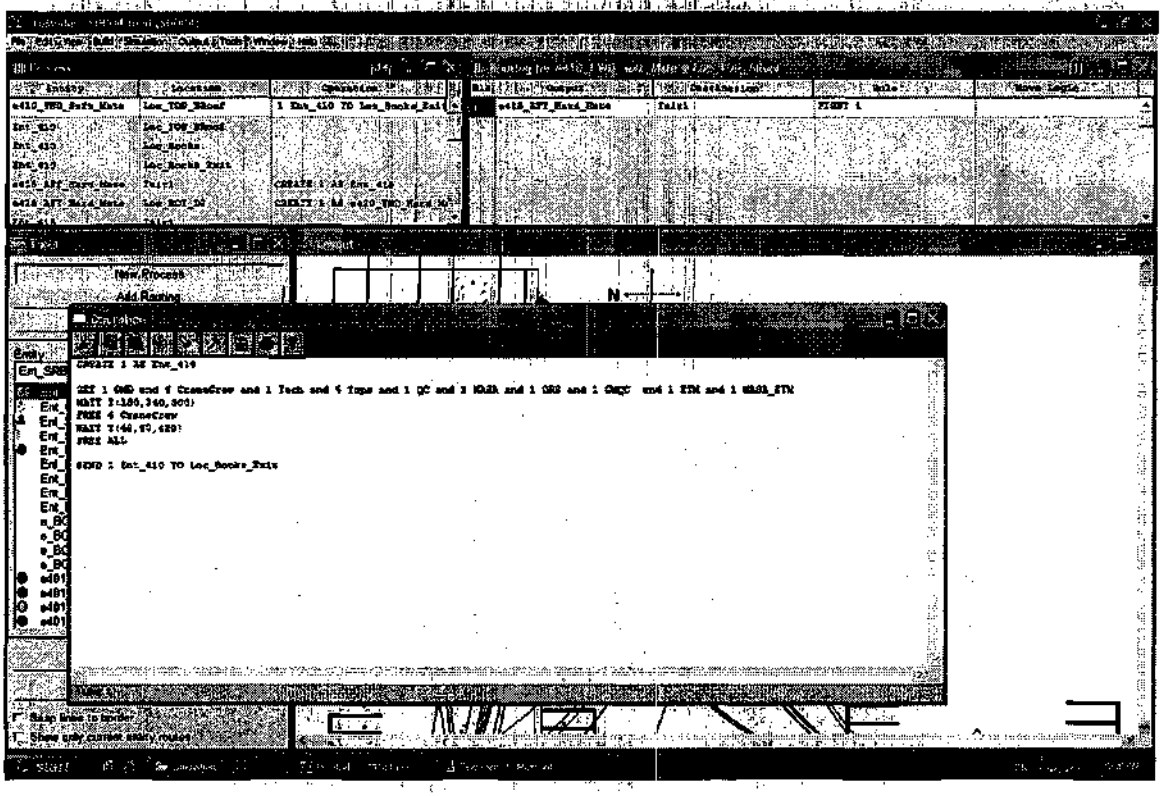


Figure 11 : ProModel (Processing Logic)

Figure 11 shows the beginning of the processing logic for this precedence relationship, which is the processing logic for S0004.410. Once completed, it exits and outputs S0004.415.

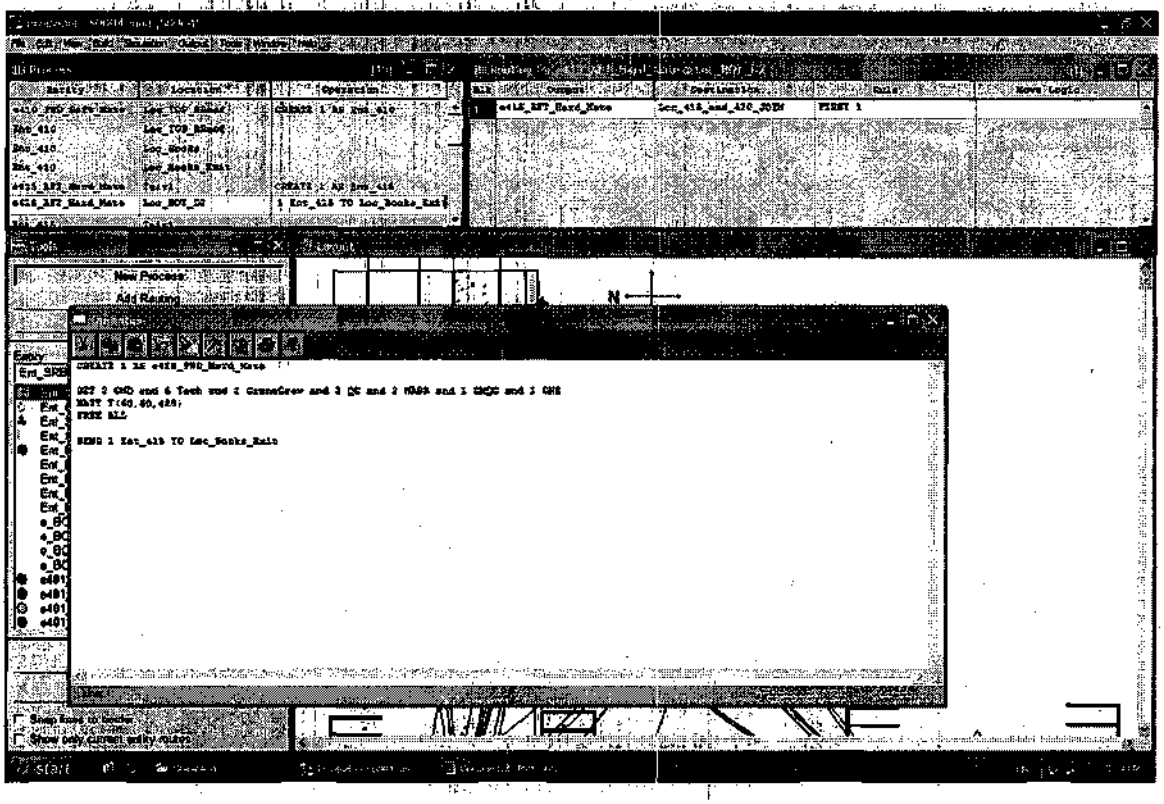


Figure 12 : ProModel (Processing Logic)

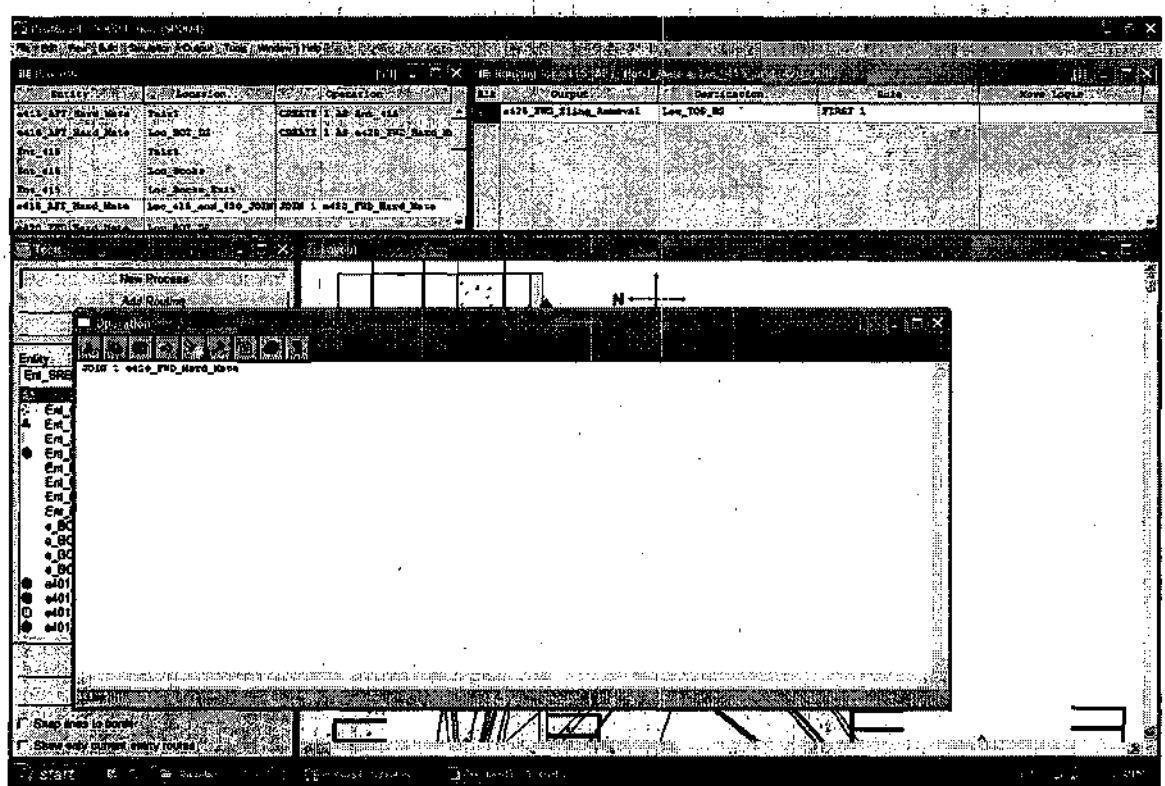


Figure 13 : ProModel (Processing Logic)

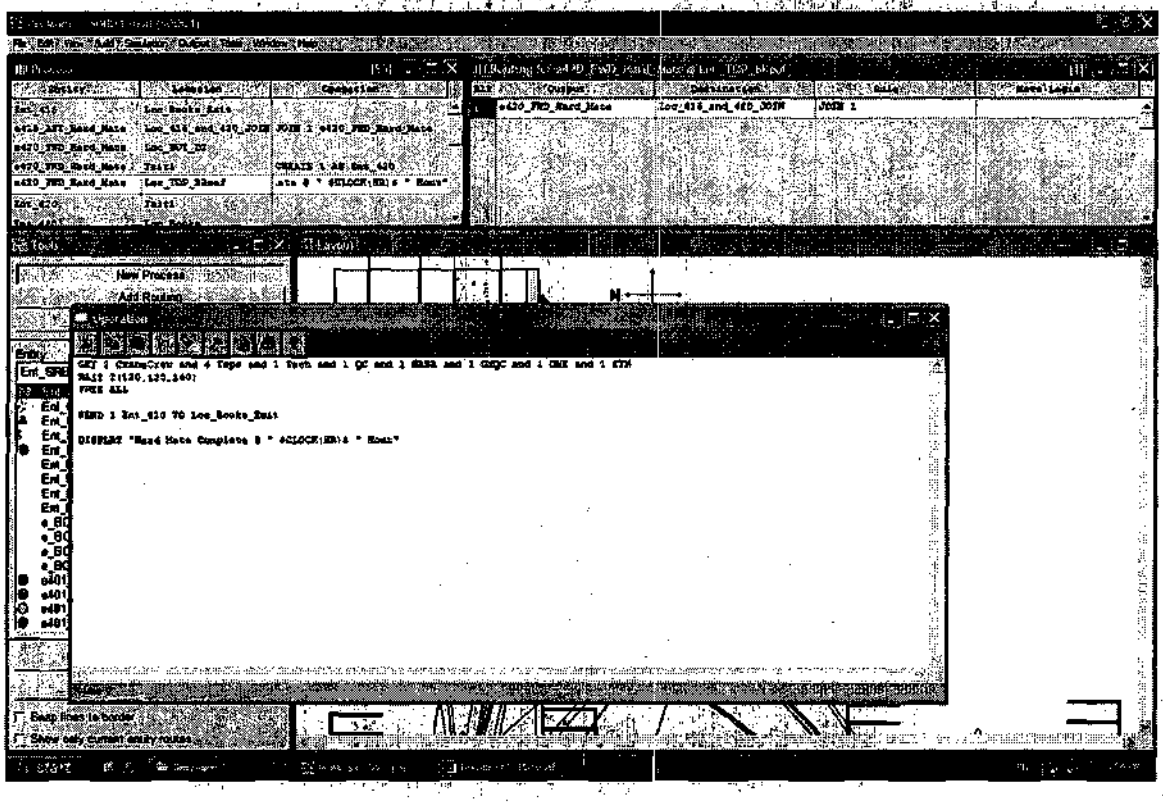


Figure 14 : ProModel (Processing Logic)

Figure 12 shows the processing logic for S0004.415. As soon as it is created, it creates S0004.420 before any of its logic is processed. The logic of S0004.415 and S0004.420 are then processed in parallel. Once S0004.415 is done processing it outputs itself to a dummy location, Loc_415_and_420_JOIN (shown in the Routing window). Figure 13 shows S0004.420 does the same. This dummy location is where both S0004.415 and S0004.420 exit upon completion. Once both entities arrive at this dummy location (Figure 14), e415_AFT_Hard_Mate joins with e420_FWD_Hard_Mate into one entity. This newly created entity is outputted as e425_FWD_Sling_Removal. Then processing logic for S0004.425 is then executed.

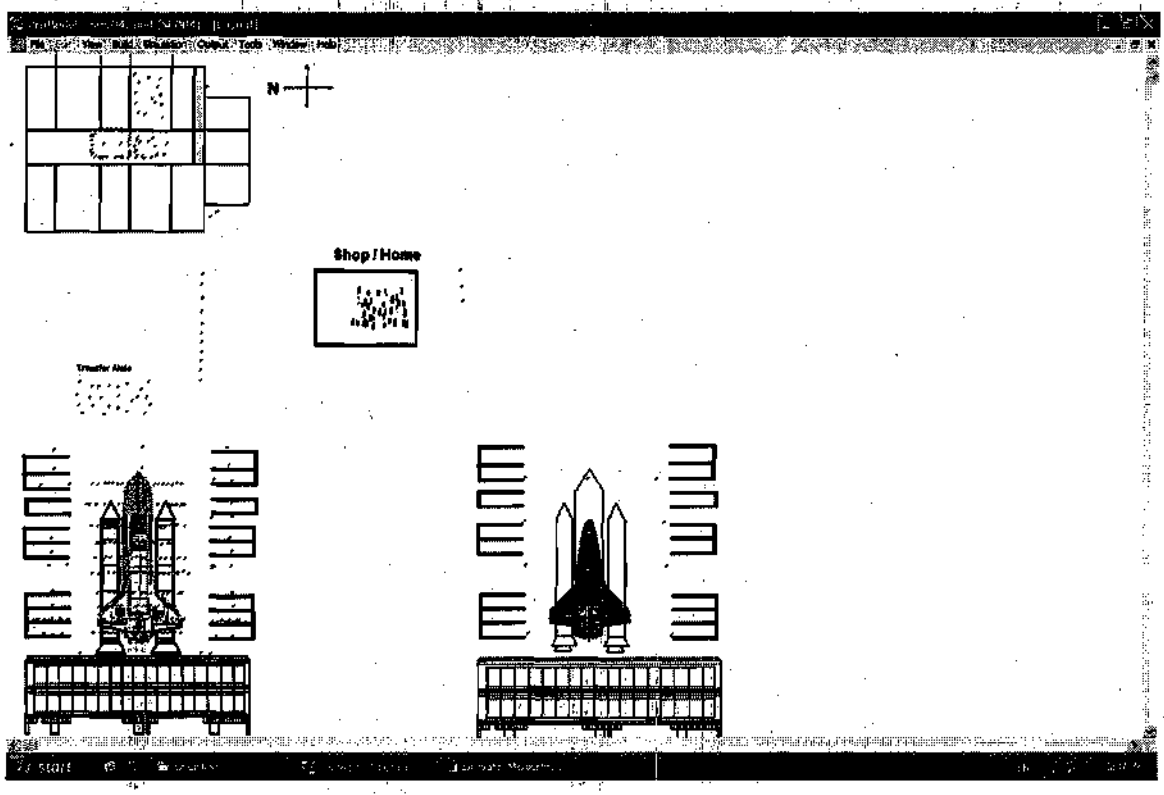


Figure 15 : ProModel (Simulation Layout)

The simulation serves as a visual representation of the S0004 process. Figure 15 shows the background of the simulation layout, which is made up of three main parts:

1. The top area is the floor plan of the VAB showing the transfer aisle, where the beginning of the S0004 process takes place.

2. The middle area is a Shop / Home area, which is the location where resources are kept when idle. The resources are all wearing different colored clothes to represent the different resource groups.

3. The bottom area show different views of the MLP, ETs, SRBs, and Orbiter. The bottom left area is a front view of the shuttle atop the MLP, and the bottom right area is a rear view with the ET and SRBs shown as transparent. The platforms, which are a part of the building's structure, are shown in blue. They extract and retract as needed in the process and the simulation visually shows this. The green box in the front view represents the Crew Module where resources go inside the

Orbiter to complete tasks. The green box in the rear view represents the AFT compartment in which resources go inside the Orbiter to complete tasks. The little red dots with white x's are separate areas of the locations in which resources go to work.

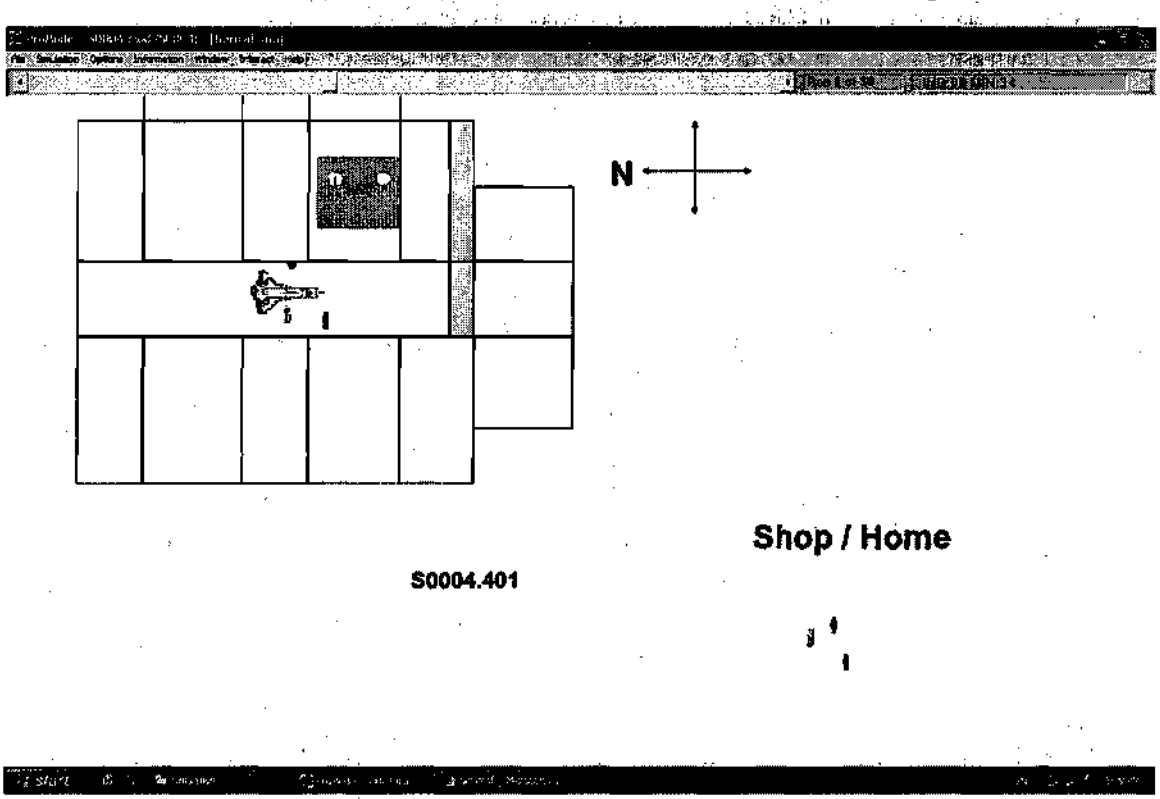


Figure 16 : ProModel (VAB floor)

Figure 16 is a zoomed-in view of the layout. Initially, S0004 tasks take place in the transfer aisle. This is the area where the Orbiter gets its sling attached. The gray square is the top of the Mobile Launch Platform with the ET and SRBs atop waiting for mate with the Orbiter. "S0004.401" shown is a representation that task S0004.401 is currently being worked in the simulation.

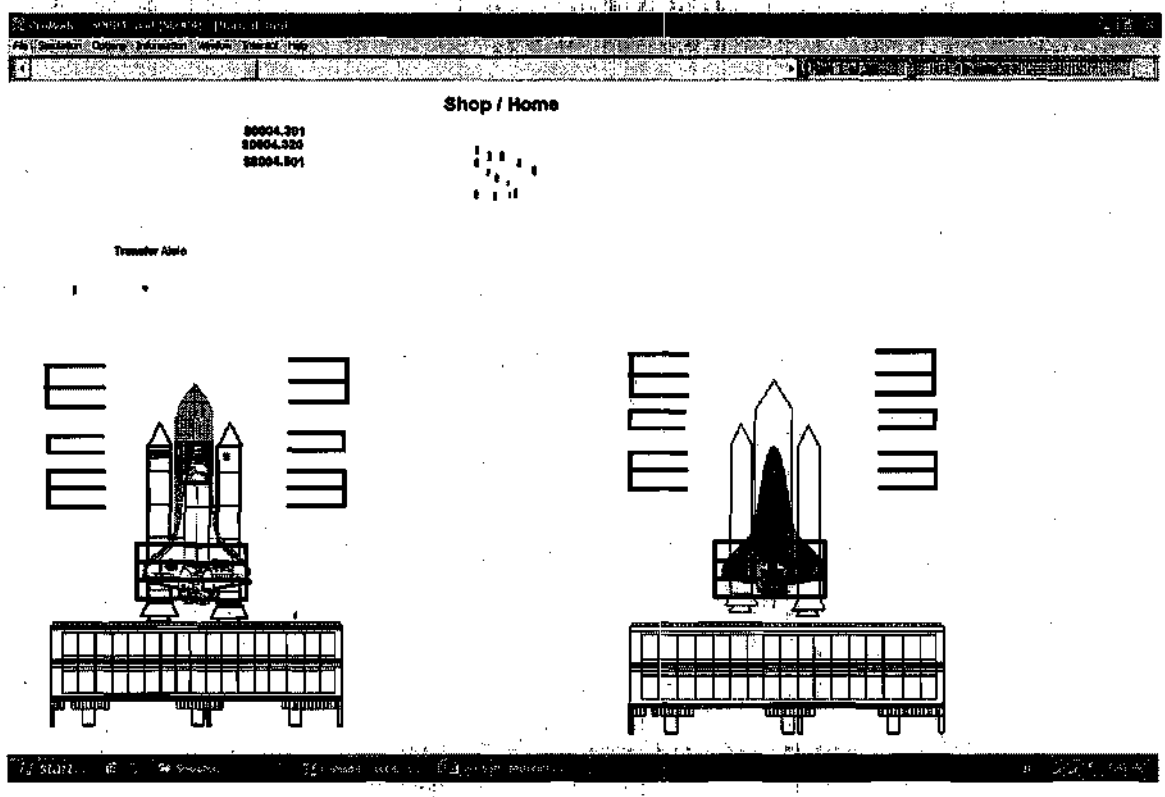


Figure 17 : ProModel (Front and Rear Views)

Figure 17 is a zoomed-in view of the portion of the layout showing the front and back views of the Mobile Launch Platform and the Shuttle. Here the bottom platforms are extracted, and the top three platforms are still retracted. Platforms are extracted to give resources access to areas where work is required. The area labeled "Transfer Aisle" is also there in this view because a few tasks are done in that location. This particular snapshot shows that S0004.301, S0004.320, and S0004.501 are all being worked at this point in time.

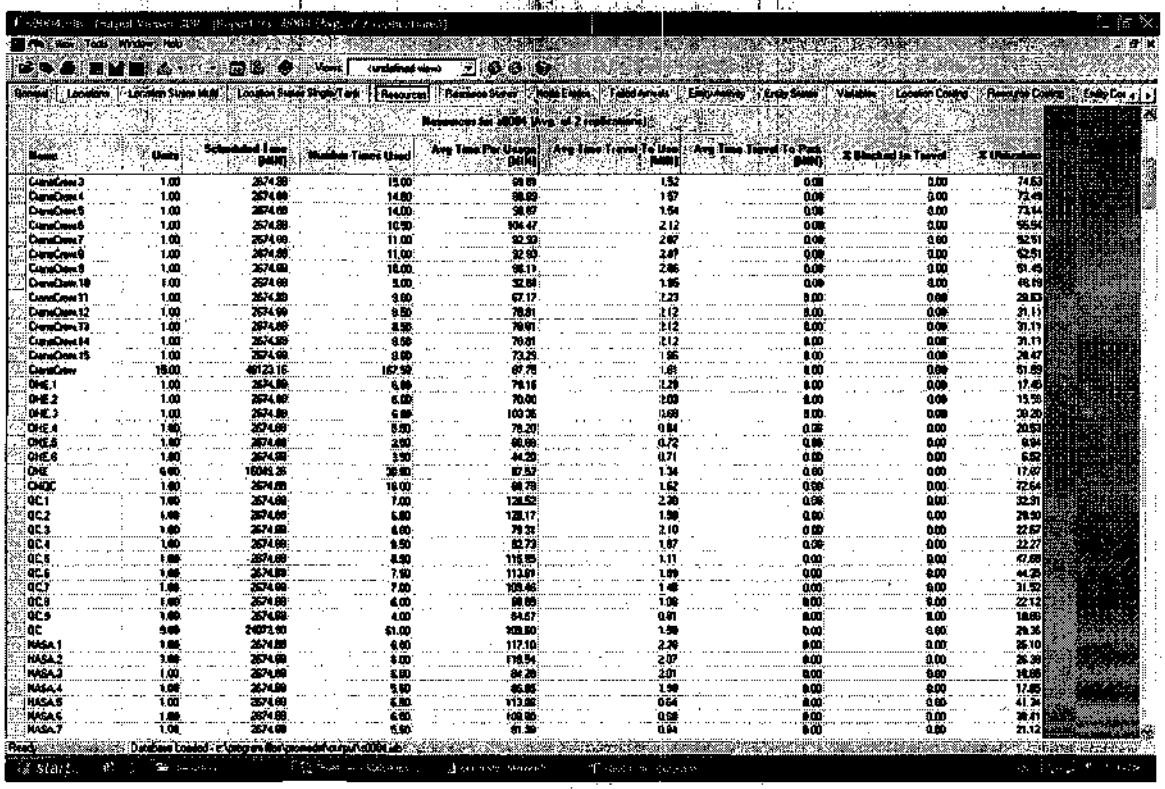


Figure 18 : ProModel (Generated Reports)

At the completion of the simulation's execution for a number of replications, ProModel generates a report showing a collection of statistics. Figure 18 shows a sheet of the report that is generated. This particular sheet is the resources sheet which shows all resources individually and collectively as a group. Data shown in the report includes: number of times used, average time per usage, average travel time per usage, and percent utilization. Such information helps to analyze the S0004 process and provide recommendations. The report generates a lot of data that is not needed for the project's purposes. Since ProModel does not save this data, the user can use and manipulate the data by exporting it to excel. In excel, the data can be customized on a run time basis. When ProModel is updated and changes are made, the simulation must be run again and reports are regenerated.

Future Considerations

Because of incomplete resource data sets, the simulation model represents the most accurate description of the S0004 process with the exceptions of resource availability. The remaining resource availability data is needed to ensure the most accurate representation of the S0004 process.

Because of several incomplete resource data sets, scenario analyses were not performed. The simulation model will output the most efficient process flow based on resource availability and scenario analyses. Once the data is collected, it is recommended that scenario analyses be performed using the simulation model. This requires minimal coding and time.

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CONTACTS

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Katrine Stelges
Greg Olive
Keith Tribble
Carl Vita

APPENDIX

Appendix A: Network Flow Model

Appendix B: Microsoft Project File

Appendix C: Subtask / Durations Spreadsheet

WAD (Subtask)	DURATION (hr)		
	Min	Most Likely	Max
S0004.401	7	9	25
OP 10 Sling Attach Preps	0.5	1	2
OP 20 Lift and Inspect Sling	0.5	0.75	1.5
OP 30 Mate Left Aft Sling to Orbiter	0.5	0.5	1.5
OP 40 Mate Right Aft Sling	0.5	1	2
OP 50 Mate Left FWD Sling	0.5	0.5	1
OP 60 Mate Right FWD Sling	0.5	0.5	1
OP 70 Raise off OTS	1.75	2	12
OP 80 Configure Orbiter for Lift	2.25	2.75	4
S0004.405	10.5	7.75	39.5
OP 10 Lowering Orbiter Through Platforms			
Alignment	0.25	1	2
Lowering	1	1.25	3
OP 20 Install turnbuckles			
Move D Platform	0.75	1.5	6
Turnbuckle installation	0.25	0.5	0.75
OP 30, 50, 60 Salad Bowl and Umbilical Inspection	0.75	1	6
OP 40 1245 Unit Reconnect	0.25	0.5	0.5
OP 70 AFT Soft mate	2	2.75	6.75
ADJ Turnbuckles till ET Strut Engaged 3 inch	0.75	1	1.5
Main Sep Bolt Build up	0.5	0.5	2
GSE Strut Removal	0.5	1	1.5
Toque Turnbuckles	0.5	0.5	1
OMD		0.5	
B platform extend	1	1.5	2
Op 80,90 Main sep bolt installation	0.5	0.5	4.5
Op 100,110 1015 Hook ups Soft mate post ops	1	1	1
Op 120 Reaction fixture Installation	0.5	0.5	1
S0004.410	4	5	6
Op 10 Platform Configuration and Debris Catcher installation			

Debris Catcher Installation	0.75	1	1.5
Op 20 Install and Align of Pointer Assembly	0.75	1	1.25
Op 30 ET FWD Attachment With GSE	0.75	1	1.25
Op 40 -y Bipod Strut to Yoke Assembly Alignment	0.75	1	1.25
Op 50 -y Bipod Attachment to Yoke	0.75	1	1.25
S0004.415 Orbiter to ET AFT Hard Mate	1	1	7
S0004.420 FWD Hard Mate	2	2	4
S0004.425 Removal of Sling Forward	2	2.5	3.5
Op 10,20 FWD sling removal and 768 removal	1	1.5	2
Op 30 Hoist Fitting Inspection and Door installation (V30-14399, V80-92701)	0.5	1	1.5
Retract B Platform	1	1.5	2
S0004.430 Aft Sling Removal	2	2.5	3.5
Safety clears and sling removal	1	1.5	2
Lower AP-65 Platform	0.5	1	2
Remove AFT cups and liners and install doors (V80-95005, V8-95006)	1	1.5	2
S0004.301 Aft Entry	6	6.5	8
Op 10 Remove GSE 50-1, 50-2 Doors and install Duct	0.5	1	1.25
Op 20,40 AFT Platform Installation and HYD Hose removal (V35-00008, V9002.119)	3	4	5
Op 30 Lights and Alarms	4	5	6
Op 50 Install Jumper duct (V1313.009	0.5	0.75	1
Op 60 PD 15, PD 16 ET Sense line Mate	0.5	0.5	1
S0004.320 MLP MPS lines Preps for Carrier Mate TSM Carrier Plate Mate		23	
V2093.002 LH2 TSM T-0 Umbilical Carrier Plate Mechanical Mates	11	12	16
V2094.002 LO2 TSM T-0 Umbilical Carrier Plate Mechanical Mates	11	12	16
V2093.003 LH2 TSM T-0 Umbilical Carrier Plate Electrical Mate	2.75	3	6
V2094.003 LO2 TSM T-0 Umbilical Carrier Plate Electrical Mate	2.75	3	6
V2093.004 LH2 TSM T-0 Umbilical Carrier Plate Post Mate Operations	2.5	3	3.5
V2094.004 LO2 TSM T-0 Umbilical Carrier Plate Post Mate Operations	2.5	3	3.5
V2093.005 LH2 TSM T-0 Umbilical Carrier Plate Peripheral Seal Installation	0.75	1	1.25
V2094.005 LO2 TSM T-0 Umbilical Carrier Plate Peripheral Seal Installation	0.75	1	1.25
S0004.325 S72-0685-01 Panel Initial Configuration and Activation	0.5	0.5	1
S0004.305 LO2/LH2 Monoball seal closeout Inspection	0.5	1	2

S0004.501 Sling Disassembly and stowage	4.5	5	6
B and E Platform Extension	2	2	4
S0004.510 FWD Attach GSE Disassembly	1.75	2	3
Nose Cap Platform Positioning	0.25	0.25	0.5
Platform Observers	0.25	0.25	0.25
S0004.315 CM Unlatching, Opening and CM Xover and Platform Installation	7.5	8.25	11
Op 10,20 Transport platforms and extend white room	1	1	2
Op 30 Orbiter FWD entry	1.5	2	2.5
Op 40 Crew compartment ingress and platform installation	2	2	3
Op 60 Perform Hatch functional	1.5	2	4
Op 120 Pyro test assy relocation	1	1	1.5
Op 160 Ground Checkout Access Door Close Out	0.25	0.25	0.5
S0004.436 LO2 Orbiter to ET umbilical Mate and Reaction fixture Removal	2.5	3	8
Op 10 Install Jack Bolts	1	1.5	3
Op 20,30 LO2 Umbilical Align, Mate and Reaction fixture Removal	1.25	1.5	3
S0004.435 LH2 Orbiter to ET umbilical mate and reaction fixture removal	3.5	4	8
Op 10, 20 LH2 Manifold Press and Jack bolt installation	1	1.5	3
Op 30,40 LH2 Umbilical align, Mate and reaction fixture removal	1.25	1.5	3
Op 50 LH2 PD 5 I/F Leak Check and Manifold Securing	0.75	1	1.25
V5029.011 LH2 Umbilical and Main Sep Bolt Ordnance Installation	4.5	5	8
V5029.012 LO2 Umbilical and Main Sep Bolt Installation	4.5	5	8
S0004.441 LH2 Orbiter to ET Umbilical Stud Tensioning	2.5	3	5.6
Op 10,20 Equipment set up and Clear set up	0.5	0.5	0.75
OP 30 Stud Pulls	1.25	1.5	2
OMD		1.5	
Op 40 Ultrasound Inspection	0.5	0.5	0.5
Op 50 Clean up and post ops	0.5	0.5	0.5
S0004.440 LO2 Orbiter to ET Umbilical stud Tensioning	2.5	3	6
Op 10,20 Equipment set up and Clear set up	0.5	0.5	0.75
OP 30 Stud Pulls	1.25	1.5	2
Op 40 Ultrasound Inspection	0.5	0.5	0.5
Op 50 Clean up and post ops	0.5	0.5	0.5
V35-50003 LH2 Flight Strut Installation	2.5	3	4

V35-50010 LO2 Flight Strut Installation	2.5	3	4
S0004.445			
Op 10 LH Monoball through first inspection	9	10	11
Op 20 LH2 Monoball Part Two, Closeout through Completion	3	4	5
S0004.450*			
Op 10 LO2 Monoball through first inspection	9	10	11
Op 20 LO2 Monoball Part Two, Closeout through Completion	3	4	5
V5029.016 UMB Can C/O Outside LO2	2.5	3	4
V5029.015 UMB Can C/O Outside LH2	2.5	3	4
S0004.310 Main Sep C/O outside RH	1	1.5	2.5
Op 10 spring and retainer install	1	1.5	2
OP 20 bolt Absorber install	0.75	1	1.5
S0004.311 Main Sep C/O outside LH	1	1.5	2.5
Op 10 spring and retainer install	1	1.5	2
OP 20 bolt Absorber install	0.75	1	1.5
V35-50004 LO2 Purge Curtain	6	12	16
V35-50005 LH2 Purge Curtain	6	12	16
V5170 ET sep Camera install and door closeout	5	5.5	8
T5550 Umbilical Foam Application			
OP 10,20,30 Spill Protection thru Mold installation	4	8	12
Op 40 Foam Application	1.5	1.5	2
Op 50 Final trim and sell	2	4	6
Op 60 Fire Barrier	4	4	4
V5029.013 LH2 Blast Can Close Out Inside	5	6	7
V5029.014 LO2 Blast Can Close Out Inside	5	6	7
V5029.021 LH2 Main Sep Bolt Blast Can Close Out Inside	1	1.5	2
V5029.020 LO2 Main Sep Bolt Blast Can Close Out Inside	1	1.5	2
V1149 T-0 Umbilicals and Orb/Et Interface Leak Checks		12.25	
Preps HUMS Routing	0.75	1	1.5
TP 8 Config	0.75	1	1.25
HUMS Chanelization	?	10.25?	?
TP 8 Leak Checks OP 50	0.75	1	1.25

LO2 ET Leak Checks OP 60	2.5	3	3.5
LH2 ET Leak Checks OP 70	2.5	3	3.5
LO2 T-0 Leak Checks OP 80	1.5	2	2.5
LH2 T-0 Leak Checks OP 90	1.5	2	2.5
Flex Hose Bagging OP 30	1	1.5	2
Mass Spec OP 130	?	12.25?	?
Gimble measurements	2	4	5

Appendix D: Complete Prototype Linear Programming Code for AMPL

INPUT

```
# options

option solver cplex;

# Parameters

param T integer;
param J integer;
param d {j in 0..J+1} integer;
set P {0..J+1} within {0..J};

set KR;
param r {j in 0..J+1, KR} integer;
param RR {KR} integer;

param EF {0..J+1} integer;
param LF {0..J+1} integer;

# Variables

var x {j in 0..J+1, EF[j]..LF[j]} binary;

# Model

minimize Makespan:
        sum {t in EF[J+1]..LF[J+1]} t * x[J+1,t];

subject to JobCompletion {j in 0..J+1}:
        sum {t in EF[j]..LF[j]} x[j,t] = 1;

subject to PrecedenceRelations {j in 1..J+1, h in P[j]}:
        sum {t in EF[h]..LF[h]} t * x[h,t] <=
        sum {t in EF[j]..LF[j]} (t-d[j]) * x[j,t];

subject to RenewableResources {k in KR, t in 1..T}:
        sum {j in 1..J}  r[j,k] *
        sum {q in max(t,EF[j])..min(t+d[j]-1, LF[j]) } x[j,q]
        <= RR[k];

data data.dat;

# Solve Problem

problem RCPSP:
```

```
x,
Makespan,
JobCompletion,
PrecedenceRelations,
RenewableResources;

solve RCPSP;

display x;
display Makespan;


minimize Makespan:
        12*x[7,12] + 13*x[7,13] + 14*x[7,14] + 15*x[7,15] + 16*x[7,16];


ampl: expand JobCompletion;
subject to JobCompletion[0]:
        x[0,0] + x[0,1] + x[0,2] + x[0,3] + x[0,4] = 1;

subject to JobCompletion[1]:
        x[1,2] + x[1,3] + x[1,4] + x[1,5] + x[1,6] = 1;

subject to JobCompletion[2]:
        x[2,1] + x[2,2] + x[2,3] + x[2,4] + x[2,5] + x[2,6] = 1;

subject to JobCompletion[3]:
        x[3,6] + x[3,7] + x[3,8] + x[3,9] + x[3,10] = 1;

subject to JobCompletion[4]:
        x[4,4] + x[4,5] + x[4,6] + x[4,7] + x[4,8] + x[4,9] + x[4,10] = 1;

subject to JobCompletion[5]:
        x[5,8] + x[5,9] + x[5,10] + x[5,11] + x[5,12] + x[5,13] + x[5,14] +
        x[5,15] + x[5,16] = 1;

subject to JobCompletion[6]:
        x[6,12] + x[6,13] + x[6,14] + x[6,15] + x[6,16] = 1;

subject to JobCompletion[7]:
        x[7,12] + x[7,13] + x[7,14] + x[7,15] + x[7,16] = 1;

ampl: expand PrecedenceRelations;
subject to PrecedenceRelations[1,0]:
        x[0,1] + 2*x[0,2] + 3*x[0,3] + 4*x[0,4] - x[1,3] - 2*x[1,4] - 3*x[1,5]
         - 4*x[1,6] <= 0;

subject to PrecedenceRelations[2,0]:
```

```
        x[0,1] + 2*x[0,2] + 3*x[0,3] + 4*x[0,4] - x[2,2] - 2*x[2,3] - 3*x[2,4]
         - 4*x[2,5] - 5*x[2,6] <= 0;

subject to PrecedenceRelations[3,1]:
        2*x[1,2] + 3*x[1,3] + 4*x[1,4] + 5*x[1,5] + 6*x[1,6] - 2*x[3,6] -
        3*x[3,7] - 4*x[3,8] - 5*x[3,9] - 6*x[3,10] <= 0;

subject to PrecedenceRelations[3,2]:
        x[2,1] + 2*x[2,2] + 3*x[2,3] + 4*x[2,4] + 5*x[2,5] + 6*x[2,6] -
        2*x[3,6] - 3*x[3,7] - 4*x[3,8] - 5*x[3,9] - 6*x[3,10] <= 0;

subject to PrecedenceRelations[4,2]:
        x[2,1] + 2*x[2,2] + 3*x[2,3] + 4*x[2,4] + 5*x[2,5] + 6*x[2,6] - x[4,4]
         - 2*x[4,5] - 3*x[4,6] - 4*x[4,7] - 5*x[4,8] - 6*x[4,9] - 7*x[4,10] <=
        0;

subject to PrecedenceRelations[5,3]:
        6*x[3,6] + 7*x[3,7] + 8*x[3,8] + 9*x[3,9] + 10*x[3,10] - 6*x[5,8] -
        7*x[5,9] - 8*x[5,10] - 9*x[5,11] - 10*x[5,12] - 11*x[5,13] - 12*x[5,14]
         - 13*x[5,15] - 14*x[5,16] <= 0;

subject to PrecedenceRelations[6,3]:
        6*x[3,6] + 7*x[3,7] + 8*x[3,8] + 9*x[3,9] + 10*x[3,10] - 6*x[6,12] -
        7*x[6,13] - 8*x[6,14] - 9*x[6,15] - 10*x[6,16] <= 0;

subject to PrecedenceRelations[6,4]:
        4*x[4,4] + 5*x[4,5] + 6*x[4,6] + 7*x[4,7] + 8*x[4,8] + 9*x[4,9] +
        10*x[4,10] - 6*x[6,12] - 7*x[6,13] - 8*x[6,14] - 9*x[6,15] - 10*x[6,16]
         <= 0;

subject to PrecedenceRelations[7,5]:
        8*x[5,8] + 9*x[5,9] + 10*x[5,10] + 11*x[5,11] + 12*x[5,12] + 13*x[5,13]
         + 14*x[5,14] + 15*x[5,15] + 16*x[5,16] - 12*x[7,12] - 13*x[7,13] -
        14*x[7,14] - 15*x[7,15] - 16*x[7,16] <= 0;

subject to PrecedenceRelations[7,6]:
        12*x[6,12] + 13*x[6,13] + 14*x[6,14] + 15*x[6,15] + 16*x[6,16] -
        12*x[7,12] - 13*x[7,13] - 14*x[7,14] - 15*x[7,15] - 16*x[7,16] <= 0;

ampl: expand RenewableResources;
subject to RenewableResources[1,1]:
        x[1,2] + 2*x[2,1] <= 3;

subject to RenewableResources[1,2]:
        x[1,2] + x[1,3] + 2*x[2,2] + 2*x[4,4] <= 3;

subject to RenewableResources[1,3]:
        x[1,3] + x[1,4] + 2*x[2,3] + 3*x[3,6] + 2*x[4,4] + 2*x[4,5] <= 3;
```

```
subject to RenewableResources[1,4]:
        x[1,4] + x[1,5] + 2*x[2,4] + 3*x[3,6] + 3*x[3,7] + 2*x[4,4] + 2*x[4,5]
         + 2*x[4,6] <= 3;

subject to RenewableResources[1,5]:
        x[1,5] + x[1,6] + 2*x[2,5] + 3*x[3,6] + 3*x[3,7] + 3*x[3,8] + 2*x[4,5]
         + 2*x[4,6] + 2*x[4,7] <= 3;

subject to RenewableResources[1,6]:
        x[1,6] + 2*x[2,6] + 3*x[3,6] + 3*x[3,7] + 3*x[3,8] + 3*x[3,9] +
        2*x[4,6] + 2*x[4,7] + 2*x[4,8] <= 3;

subject to RenewableResources[1,7]:
        3*x[3,7] + 3*x[3,8] + 3*x[3,9] + 3*x[3,10] + 2*x[4,7] + 2*x[4,8] +
        2*x[4,9] + x[5,8] + x[6,12] <= 3;

subject to RenewableResources[1,8]:
        3*x[3,8] + 3*x[3,9] + 3*x[3,10] + 2*x[4,8] + 2*x[4,9] + 2*x[4,10] +
        x[5,8] + x[5,9] + x[6,12] + x[6,13] <= 3;

subject to RenewableResources[1,9]:
        3*x[3,9] + 3*x[3,10] + 2*x[4,9] + 2*x[4,10] + x[5,9] + x[5,10] +
        x[6,12] + x[6,13] + x[6,14] <= 3;

subject to RenewableResources[1,10]:
        3*x[3,10] + 2*x[4,10] + x[5,10] + x[5,11] + x[6,12] + x[6,13] + x[6,14]
         + x[6,15] <= 3;

subject to RenewableResources[1,11]:
        x[5,11] + x[5,12] + x[6,12] + x[6,13] + x[6,14] + x[6,15] + x[6,16] <=
        3;

subject to RenewableResources[1,12]:
        x[5,12] + x[5,13] + x[6,12] + x[6,13] + x[6,14] + x[6,15] + x[6,16] <=
        3;

subject to RenewableResources[1,13]:
        x[5,13] + x[5,14] + x[6,13] + x[6,14] + x[6,15] + x[6,16] <= 3;

subject to RenewableResources[1,14]:
        x[5,14] + x[5,15] + x[6,14] + x[6,15] + x[6,16] <= 3;

subject to RenewableResources[1,15]:
        x[5,15] + x[5,16] + x[6,15] + x[6,16] <= 3;

subject to RenewableResources[1,16]:
        x[5,16] + x[6,16] <= 3;
```

OUTPUT

```
CPLEX 8.0.0: optimal integer solution; objective 14
34 MIP simplex iterations
0 branch-and-bound nodes
x [*,*] (tr)
:   0  1  2  3  4  5  6  7  :=
0   1  .  .  .  .  .  .  .
1   0  .  1  .  .  .  .  .
2   0  1  0  .  .  .  .  .
3   0  0  0  .  .  .  .  .
4   0  0  0  .  1  .  .  .
5   .  0  0  .  0  .  .  .
6   .  0  0  0  0  .  .  .
7   .  .  .  0  0  .  .  .
8   .  .  .  1  0  0  .  .
9   .  .  .  0  0  0  .  .
10  .  .  .  0  0  0  .  .
11  .  .  .  .  .  0  .  .
12  .  .  .  .  .  1  0  0
13  .  .  .  .  .  0  0  0
14  .  .  .  .  .  0  1  1
15  .  .  .  .  .  0  0  0
16  .  .  .  .  .  0  0  0
;
```

Makespan = 14

Appendix E : Complete S0004 Linear Programming Code for AMPL

INPUT

```
# Parameters

param T;
param J;
param d {j in 0..J+1};
set P {0..J+1} within {0..J};

set KR;
param r {j in 0..J+1, KR};
param RR {KR};

param EF {0..J+1};
param LF {0..J+1};

# Variables

var x {j in 0..J+1, EF[j]..LF[j]} binary;

# Model

minimize Makespan:
        sum {t in EF[J+1]..LF[J+1]} t * x[J+1,t];

subject to JobCompletion {j in 0..J+1}:
        sum {t in EF[j]..LF[j]} x[j,t] = 1;

subject to PrecedenceRelations {j in 1..J+1, h in P[j]}:
        sum {t in EF[h]..LF[h]} t * x[h,t] <= sum {t in EF[j]..LF[j]} (t-d[j]) * x[j,t];

subject to RenewableResources {k in KR, t in 1..T}:
        sum {j in 1..J}  r[j,k] * sum {q in max(t,EF[j])..min(t+d[j]-1, LF[j]) } x[j,q]        <=
RR[k];

# Solve Problem

problem RCPSP:
x,
Makespan,
JobCompletion,
PrecedenceRelations,
RenewableResources;

data ;
```

Latest Finish Time and Total Number of Steps

param T 480;
param J 113;

duration times for each step

param d :=
[0] 0
[1] 4
[2] 3
[3] 2
[4] 4
[5] 2
[6] 2
[7] 4
[8] 5
[9] 2
[10] 1
[11] 6
[12] 2
[13] 1
[14] 5
[15] 6
[16] 2
[17] 4
[18] 2
[19] 3
[20] 2
[21] 2
[22] 2
[23] 4
[24] 2
[25] 4
[26] 2
[27] 4
[28] 4
[29] 4
[30] 4
[31] 4
[32] 4
[33] 8
[34] 4
[35] 2

[36] 4
[37] 4
[38] 2
[39] 4
[40] 4
[41] 12
[42] 20
[43] 2
[44] 2
[45] 48
[46] 48
[47] 12
[48] 12
[49] 12
[50] 12
[51] 4
[52] 4
[53] 2
[54] 4
[55] 20
[56] 8
[57] 8
[58] 1
[59] 4
[60] 8
[61] 8
[62] 8
[63] 4
[64] 1
[65] 6
[66] 6
[67] 6
[68] 6
[69] 4
[70] 20
[71] 20
[72] 2
[73] 6
[74] 2
[75] 2
[76] 2
[77] 6
[78] 2
[79] 2
[80] 12
[81] 12
[82] 40
[83] 40

[84] 16
[85] 16
[86] 12
[87] 12
[88] 6
[89] 4
[90] 6
[91] 4
[92] 48
[93] 48
[94] 22
[95] 16
[96] 6
[97] 8
[98] 12
[99] 24
[100] 24
[101] 4
[102] 4
[103] 4
[104] 4
[105] 41
[106] 4
[107] 12
[108] 12
[109] 8
[110] 8
[111] 4
[112] 49
[113] 16
[114] 0;

Precedence Relationships

set P [0] := ;
set P [1] := 0;
set P [2] := 1;
set P [3] := 2;
set P [4] := 3;
set P [5] := 4;
set P [6] := 5;
set P [7] := 6;
set P [8] := 6;
set P [9] := 8;
set P [10] := 9;
set P [11] := 10;

```
set P [12]  :=  11;
set P [13]  :=  12;
set P [14]  :=  13;
set P [15]  :=  14;
set P [16]  :=  15;
set P [17]  :=  16;
set P [18]  :=  16;
set P [19]  :=  17;
set P [20]  :=  17;
set P [21]  :=  19;
set P [22]  :=  21;
set P [23]  :=  22;
set P [24]  :=  22;
set P [25]  :=  24;
set P [26]  :=  24;
set P [27]  :=  23;
set P [28]  :=  27;
set P [29]  :=  28;
set P [30]  :=  29;
set P [31]  :=  30;
set P [32]  :=  31;
set P [33]  :=  31;
set P [34]  :=  33;
set P [35]  :=  34;
set P [36]  :=  35;
set P [37]  :=  36;
set P [38]  :=  37;
set P [39]  :=  38;
set P [40]  :=  38;
set P [41]  :=  40;
set P [42]  :=  40;
set P [43]  :=  42;
set P [44]  :=  42;
set P [45]  :=  37;
set P [46]  :=  37;
set P [47]  :=  45;
set P [48]  :=  46;
set P [49]  :=  47;
set P [50]  :=  48;
set P [51]  :=  49;
set P [52]  :=  50;
set P [53]  :=  51 52;
set P [54]  :=  44;
set P [55]  :=  38;
set P [56]  :=  55;
set P [57]  :=  56;
set P [58]  :=  57;
set P [59]  :=  57;
```

```
set P [60]  :=  59;
set P [61]  :=  60;
set P [62]  :=  61;
set P [63]  :=  62;
set P [64]  :=  63;
set P [65]  :=  54;
set P [66]  :=  65;
set P [67]  :=  54;
set P [68]  :=  67;
set P [69]  :=  68;
set P [70]  :=  69;
set P [71]  :=  69;
set P [72]  :=  70;
set P [73]  :=  72;
set P [74]  :=  73;
set P [75]  :=  74;
set P [76]  :=  71;
set P [77]  :=  76;
set P [78]  :=  77;
set P [79]  :=  78;
set P [80]  :=  73;
set P [81]  :=  77;
set P [82]  :=  80;
set P [83]  :=  81;
set P [84]  :=  82;
set P [85]  :=  83;
set P [86]  :=  79;
set P [87]  :=  75;
set P [88]  :=  79;
set P [89]  :=  79;
set P [90]  :=  75;
set P [91]  :=  75;
set P [92]  :=  87;
set P [93]  :=  86;
set P [94]  :=  75 79;
set P [95]  :=  92 93;
set P [96]  :=  92 93;
set P [97]  :=  92 93;
set P [98]  :=  92 93;
set P [99]  :=  75;
set P [100] :=  79;
set P [101] :=  79;
set P [102] :=  79;
set P [103] :=  84 85;
set P [104] :=  84 85;
set P [105] :=  84 85;
set P [106] :=  84 85;
set P [107] :=  84 85;
```

```
set P  [108]  :=      84 85;
set P  [109]  :=      84 85;
set P  [110]  :=      84 85;
set P  [111]  :=      84 85;
set P  [112]  :=      84 85;
set P  [113]  :=      84 85;
set P  [114]  :=      7 18 20 25 26 32 39 41 43 53 58 64 66 88
                      89 90 91 94 95 96 97 98 99 100 101 102 103
                      104 105 106 107 108 109 110 111 112 113;


# Types of Skills

set KR := 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27;

# Resources consumed at each step

param r :=

# Tech

[0,1] 0
[1,1] 8
[2,1] 9
[3,1] 9
[4,1] 7
[5,1] 5
[6,1] 3
[7,1] 3
[8,1] 3
[9,1] 5
[10,1] 3
[11,1] 5
[12,1] 0
[13,1] 0
[14,1] 23
[15,1] 2
[16,1] 6
[17,1] 4
[18,1] 1
[19,1] 6
[20,1] 4
[21,1] 0
[22,1] 6
[23,1] 0
[24,1] 5
[25,1] 6
```

[26,1] 4
[27,1] 1
[28,1] 1
[29,1] 1
[30,1] 1
[31,1] 1
[32,1] 5
[33,1] 1
[34,1] 7
[35,1] 2
[36,1] 0
[37,1] 7
[38,1] 0
[39,1] 2
[40,1] 6
[41,1] 6
[42,1] 2
[43,1] 2
[44,1] 2
[45,1] 0
[46,1] 0
[47,1] 0
[48,1] 0
[49,1] 0
[50,1] 0
[51,1] 0
[52,1] 0
[53,1] 0
[54,1] 1
[55,1] 6
[56,1] 0
[57,1] 0
[58,1] 0
[59,1] 1
[60,1] 2
[61,1] 4
[62,1] 2
[63,1] 1
[64,1] 1
[65,1] 4
[66,1] 4
[67,1] 4
[68,1] 4
[69,1] 2
[70,1] 2
[71,1] 2
[72,1] 2
[73,1] 2

[74,1] 0
[75,1] 2
[76,1] 2
[77,1] 2
[78,1] 0
[79,1] 2
[80,1] 1
[81,1] 1
[82,1] 1
[83,1] 1
[84,1] 1
[85,1] 1
[86,1] 4
[87,1] 4
[88,1] 1
[89,1] 0
[90,1] 1
[91,1] 0
[92,1] 2
[93,1] 2
[94,1] 0
[95,1] 4
[96,1] 4
[97,1] 4
[98,1] 2
[99,1] 1
[100,1] 1
[101,1] 1
[102,1] 1
[103,1] 2
[104,1] 1
[105,1] 1
[106,1] 1
[107,1] 1
[108,1] 1
[109,1] 1
[110,1] 0
[111,1] 1
[112,1] 1
[113,1] 1
[114,1] 0

OMD

[0,2] 0
[1,2] 2
[2,2] 2
[3,2] 2

[4,2] 2
[5,2] 2
[6,2] 2
[7,2] 0
[8,2] 2
[9,2] 2
[10,2] 2
[11,2] 2
[12,2] 4
[13,2] 2
[14,2] 4
[15,2] 1
[16,2] 2
[17,2] 2
[18,2] 0
[19,2] 2
[20,2] 0
[21,2] 0
[22,2] 2
[23,2] 0
[24,2] 2
[25,2] 0
[26,2] 0
[27,2] 1
[28,2] 1
[29,2] 1
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[32,2] 2
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[47,2] 0
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[50,2] 0
[51,2] 0

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CMCQ

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[108,3] 1
[109,3] 1
[110,3] 1
[111,3] 0
[112,3] 1
[113,3] 0
[114,3] 0

CRANE CREW

[0,4] 0
[1,4] 10
[2,4] 10
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[4,4] 10
[5,4] 10
[6,4] 10
[7,4] 0

[8,4] 10
[9,4] 10
[10,4] 10
[11,4] 10
[12,4] 9
[13,4] 9
[14,4] 14
[15,4] 14
[16,4] 3
[17,4] 3
[18,4] 0
[19,4] 5
[20,4] 0
[21,4] 0
[22,4] 5
[23,4] 7
[24,4] 2
[25,4] 0
[26,4] 0
[27,4] 6
[28,4] 6
[29,4] 6
[30,4] 6
[31,4] 2
[32,4] 2
[33,4] 2
[34,4] 6
[35,4] 0
[36,4] 7
[37,4] 6
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[54,4] 0
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[57,4] 0
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[110,4] 0
[111,4] 0
[112,4] 0
[113,4] 0
[114,4] 0

ETM

[0,5] 0
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[3,5] 0
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T OPS TECH

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TRANSPORTER CREW

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USA SAFETY

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UNUSED RESOURCE MAY BE NEEDED

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UNUSED RESOURCE MAY BE NEEDED

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[110,27] 0
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[112,27] 0
[113,27] 0
[114,27] 0;

Number of a Skill available per shift

param RR :=
Tech
[1] 42
OMD

[2] 10
CMCQ
[3] 11
CRANE CREW
[4] 30
ETM
[5] 3
FLIGHT CREW SYSTEMS QC
[6] 2
FLIGHT CREW SYSTEMS TECH
[7] 9
HEAVY EQUIPMENT
[8] 14
LAUNCH ACCESSORIES ENGINEERING
[9] 2
MLP TECH
[10] 38
MPS
[11] 3
NASA ETM
[12] 3
NASA OEL ENG
[13] 2
NASA QA
[14] 18
NDE QE
[15] 2
NDE TECH
[16] 8
OEL ENG
[17] 4
OHE
[18] 6
OMD
[19] 10
QC
[20] 21
PYRO ENG
[21] 5
T OPS QC
[22] 26
T OPS TECH
[23] 50
TRANSPORTER CREW
[24] 6
USA SAFETY
[25] 9
UNUSED RESOURCE

[26] 10
UNUSED RESOURCE
[27] 10;

Earliest Finish for each Step

param EF :=

[0] 0
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[3] 9
[4] 13
[5] 15
[6] 17
[7] 21
[8] 22
[9] 24
[10] 25
[11] 31
[12] 33
[13] 34
[14] 39
[15] 45
[16] 47
[17] 51
[18] 49
[19] 54
[20] 53
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[22] 58
[23] 62
[24] 60
[25] 64
[26] 62
[27] 66
[28] 70
[29] 74
[30] 78
[31] 82
[32] 86
[33] 90
[34] 94
[35] 96
[36] 100
[37] 104
[38] 106
[39] 110

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[111] 252
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[113] 264
[114] 297;

Latest Finish For each Step

param LF :=

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[16] 347
[17] 351
[18] 480
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[23] 362
[24] 476
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[32] 480
[33] 390
[34] 394
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[37] 404
[38] 413
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[109] 480

```
[110]  480
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[112]  480
[113]  480
[114]  480;


solve RCPSP;


display Makespan;
option omit_zero_rows 1, omit_zero_cols 1;
display x;
```

OUTPUT

Makespan = 297

```
ampl: ampl: x [*,*] (tr)
:    0  1   2  3  4   5  6  7  8  9 10 11 12 13 14 15 16 17 18 :=
0    1  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .
4    0  1  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .
7    0  0  1  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .
9    0  0  0  1  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .
13   0  0  0  0  1  .  .  .  .  .  .  .  .  .  .  .  .  .  .
15   0  0  0  0  0  1  .  .  .  .  .  .  .  .  .  .  .  .  .
17   0  0  0  0  0  0  1  .  .  .  .  .  .  .  .  .  .  .  .
21   0  0  0  0  0  0  0  1  .  .  .  .  .  .  .  .  .  .  .
22   0  0  0  0  0  0  0  0  1  .  .  .  .  .  .  .  .  .  .
24   0  0  0  0  0  0  0  0  0  1  .  .  .  .  .  .  .  .  .
25   0  0  0  0  0  0  0  0  0  0  1  .  .  .  .  .  .  .  .
31   0  0  0  0  0  0  0  0  0  0  0  1  .  .  .  .  .  .  .
33   0  0  0  0  0  0  0  0  0  0  0  0  1  .  .  .  .  .  .
34   0  0  0  0  0  0  0  0  0  0  0  0  0  1  .  .  .  .  .
39   0  0  0  0  0  0  0  0  0  0  0  0  0  0  1  .  .  .  .
45   0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  1  .  .  .
47   0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  1  .  .
49   0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  .  1
51   0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  1  0

:    19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 :=
54   1  0  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .
56   0  0  1  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .
58   0  0  0  1  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .
60   0  0  0  0  .  1  .  .  .  .  .  .  .  .  .  .  .  .  .
62   0  0  0  0  1  0  .  1  .  .  .  .  .  .  .  .  .  .  .
66   0  0  0  0  0  0  0  0  1  .  .  .  .  .  .  .  .  .  .
70   0  0  0  0  0  0  0  0  0  1  .  .  .  .  .  .  .  .  .
```

USA
United Space Alliance

74	0	0	0	0	0	0	0	0	0	0	1	.	.	.	.	.	.		
78	0	0	0	0	0	0	0	0	0	0	0	1	.	.	.	.	.		
82	0	0	0	0	0	0	0	0	0	0	0	0	1	.	.	.	.	.	
86	0	0	0	0	0	0	0	0	0	0	0	0	0	1	.	.	.	.	
90	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	.	.	.	
94	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	.	.	.
96	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	.	.
100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	.
104	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
127	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
225	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0

:	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56 :=
106	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.				
110	0	1	1	.	.	.	.	.	.	.	.	.	.	.	.	.			
126	0	0	0	0	.	.	.	.	.	.	.	.			.	.	.	1	.
130	0	0	0	0	1	.	.	.	.	.	.	.				.	.	0	.
132	0	0	0	0	0	1	1	.	.	.	.	.				.	.	0	.
134	0	0	0	0	0	0	0	.	.	.	.	.			.	.	.	0	1
136	0	0	0	0	0	0	0	.	.	.	.	.	.			.	1	0	0
152	0	0	0	0	0	0	0	1	0	.	.	.	.	.		.	0	0	0
164	0	0	0	0	0	0	0	0	0	1	0	.	.	.	.		0	0	0
176	0	0	0	0	0	0	0	0	0	0	0	1	0	.	.	.	0	0	0
180	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	.	0	0	0
191	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
236	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
279	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
291	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
295	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
297	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0

:	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75 :=
142	1	.	.	.	.	.	.		1	.	1	.	.	.	.	.	.		
143	0	1	.	.	.	.	.		0	.	0	.	.	.	.	.	.		
146	0	0	1	.	.	.		.	0	.	0	.	.	.	.	.	.		
148	0	0	0	.	.	.	.		0	1	0	1	.	.	.	.	.		
152	0	0	0	.	.	.	.		0	0	0	0	1	.	.	.	.		
154	0	0	0	1	.	.	.		0	0	0	0	0	.	.	.	.		
162	0	0	0	0	1	.	.	.	0	0	0	0	0	.	.	.	.		
170	0	0	0	0	0	1	.	.	0	0	0	0	0	.	.	.	.		
172	0	0	0	0	0	0	.	.	0	0	0	0	0	1	1	.	.	.	
174	0	0	0	0	0	0	0	.	0	0	0	0	0	0	0	1	.	.	.
180	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	.	.
181	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	.	.
182	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	.
184	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
297	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0

```
:  76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 :=
174  1  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .
180  0  1  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .
182  0  0  1  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .
184  0  0  0  1  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .
188  0  0  0  0  .  .  .  .  .  .  .  .  .  1  .  1  .  .  .  .
190  0  0  0  0  .  .  .  .  .  .  .  .  1  0  1  0  .  .  .  .
192  0  0  0  0  1  1  .  .  .  .  .  .  0  0  0  0  .  .  .  .
196  0  0  0  0  0  0  .  .  .  .  .  1  1  0  0  0  0  .  .  .
206  0  0  0  0  0  0  .  .  .  .  .  0  0  0  0  0  0  .  .  1
232  0  0  0  0  0  0  1  1  .  .  .  0  0  0  0  0  0  .  .  0
244  0  0  0  0  0  0  0  0  .  .  .  0  0  0  0  0  0  1  1  0
248  0  0  0  0  0  0  0  0  0  1  1  0  0  0  0  0  0  0  0  0

:     95 96  97  98  99 100 101 102 103  104 105 106 107 108 109 110 111 112 113 :=
188  .  .  .  .  .  .  1  1  .  .  .  .  .  .  .  .  .  .  .  .
208  .  .  .  .  .  1  1  0  0  .  .  .  .  .  .  .  .  .  .  .
250  .  1  .  .  .  0  0  0  0  .  .  .  .  .  .  .  .  .  .  .
252  .  0  1  .  .  0  0  0  0  0  0  .  1  .  .  .  .  0  .  .
256  .  0  0  1  .  0  0  0  0  0  0  .  0  .  .  .  0  0  0  .  .
260  1  0  0  0  0  0  0  0  0  0  0  .  0  0  1  0  0  0  .  .
263  0  0  0  0  0  0  0  0  0  0  0  .  0  0  0  0  1  0  .  .
264  0  0  0  0  0  0  0  0  0  0  1  .  0  0  0  0  0  0  .  0
279  0  0  0  0  0  0  0  0  0  0  0  .  0  1  0  0  0  0  .  1
286  0  0  0  0  0  0  0  0  0  0  0  .  0  0  0  0  0  1  .  0
288  0  0  0  0  0  0  0  0  0  1  0  .  0  0  0  0  0  0  .  0
289  0  0  0  0  0  0  0  0  0  0  0  1  0  0  0  0  0  0  .  0
297  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  1  0  0  1  0

:   114  :=
297   1
```

Appendix F : Schedule

i	STEP	Duration (hours)	Start Time (hours)	Completion Time (hours)		
1	OP 10 Sling Attach Preps	1	0	1	4	60
2	OP 20 Lift and Inspect Sling	0.75	1	1.75	7	105
3	OP 30 Mate Left Aft Sling to Orbiter	0.5	1.75	2.25	9	135
4	OP 40 Mate Right Aft Sling	1	2.25	3.25	13	195
5	OP 50 Mate Left FWD Sling	0.5	3.25	3.75	15	225
6	OP 60 Mate Right FWD Sling	0.5	3.75	4.25	17	255
7	Set up Safety Clears	1	4.25	5.25	21	315
8	Remove FWD OTS	1.25	4.25	5.5	22	330
9	Remove Aft OTS	0.5	5.5	6	24	360
10	Take Orbiter Vertical	0.25	6	6.25	25	375
11	Spreader Beam Removal	1.5	6.25	7.75	31	465
12	Lift to High Bay	0.5	7.75	8.25	33	495
13	Alignment	0.25	8.25	8.5	34	510
14	Lowering	1.25	8.5	9.75	39	585
15	Move D Platform	1.5	9.75	11.25	45	675
16	Turnbuckle installation	0.5	11.25	11.75	47	705
17	OP 30, 50, 60 Salad Bowl and Umbilical Inspection	1	11.75	12.75	51	765
18	OP 40 1245 Unit Reconnect	0.5	11.75	12.25	49	735
19	ADJ Turnbuckles till ET Strut Engaged 3 inch	0.75	12.75	13.5	54	810
20	Main Sep Bolt Build up	0.5	31.25	31.75	127	1905
21	GSE Strut Removal	0.5	13.5	14	56	840
22	Toque Turnbuckles	0.5	14	14.5	58	870
23	B platform extend	1	14.5	15.5	62	930
24	Op 80,90 Main sep bolt installation	0.5	14.5	15	60	900
25	Op 100,110 1015 Hook ups Soft mate post ops	1	55.25	56.25	225	3375
26	Op 120 Reaction fixture Installation	0.5	15	15.5	62	930
27	Debris Catcher Installation	1	15.5	16.5	66	990
28	Op 20 Install and Align of Pointer Assembly	1	16.5	17.5	70	1050
29	Op 30 ET FWD Attachment With GSE	1	17.5	18.5	74	1110
30	Op 40 -y Bipod Strut to Yoke Assembly Alignment	1	18.5	19.5	78	1170

31	Op 50 -y Bipod Attachment to Yoke	1	19.5	20.5	82	1230
32	S0004.415 Orbiter to ET AFT Hard Mate	1	20.5	21.5	86	1290
33	S0004.420 FWD Hard Mate	2	20.5	22.5	90	1350
34	Op 10,20 FWD sling removal and 768 removal	1	22.5	23.5	94	1410
35	Op 30 Hoist Fitting Inspection and Door installation (V30-14399, V80-92701)	0.5	23.5	24	96	1440
36	Retract B Platform	1	24	25	100	1500
37	Safety clears and sling removal	1	25	26	104	1560
38	Lower AP-65 Platform	0.5	26	26.5	106	1590
39	Remove AFT cups and liners and install doors (V80-95005, V8-95006)	1	26.5	27.5	110	1650
40	Op 10 Remove GSE 50-1, 50-2 Doors and install Duct	1	26.5	27.5	110	1650
41	Op 20,40 AFT Platform Installation and HYD Hose removal (V35-00008, V9002.119)	3	44.75	47.75	191	2865
42	Op 30 Lights and Alarms	5	27.5	32.5	130	1950
43	Op 50 Install Jumper duct (V1313.009	0.5	32.5	33	132	1980
44	Op 60 PD 15, PD 16 ET Sense line Mate	0.5	32.5	33	132	1980
45	V2093.002 LH2 TSM T-0 Umbilical Carrier Plate Mechanical Mates	12	26	38	152	2280
46	V2094.002 LO2 TSM T-0 Umbilical Carrier Plate Mechanical Mates	12	47	59	236	3540
47	V2093.003 LH2 TSM T-0 Umbilical Carrier Plate Electrical Mate	3	38	41	164	2460
48	V2094.003 LO2 TSM T-0 Umbilical Carrier Plate Electrical Mate	3	66.75	69.75	279	4185
49	V2093.004 LH2 TSM T-0 Umbilical Carrier Plate Post Mate Operations	3	41	44	176	2640
50	V2094.004 LO2 TSM T-0 Umbilical Carrier Plate Post Mate Operations	3	69.75	72.75	291	4365
51	V2093.005 LH2 TSM T-0 Umbilical Carrier Plate Peripheral Seal Installation	1	44	45	180	2700
52	V2094.005 LO2 TSM T-0 Umbilical Carrier Plate Peripheral Seal Installation	1	72.75	73.75	295	4425
53	S0004.325 S72-0685-01 Panel Initial Configuration and Activation	0.5	73.75	74.25	297	4455
54	S0004.305 LO2/LH2 Monoball seal closeout Inspection	1	33	34	136	2040
55	S0004.501 Sling Disassembly and stowage	5	26.5	31.5	126	1890
56	B and E Platform Extension	2	31.5	33.5	134	2010
57	S0004.510 FWD Attach GSE Disassembly	2	33.5	35.5	142	2130
58	Nose Cap Platform Positioning	0.25	35.5	35.75	143	2145
59	Op 10,20 Transport platforms and extend white room	1	35.5	36.5	146	2190
60	Op 30 Orbiter FWD entry	2	36.5	38.5	154	2310
61	Op 40 Crew compartment ingress and platform installation	2	38.5	40.5	162	2430
62	Op 60 Perform Hatch functional	2	40.5	42.5	170	2550
63	Op 120 Pyro test assy relocation	1	44.25	45.25	181	2715
64	Op 160 Ground Checkout Access Door Close Out	0.25	74	74.25	297	4455
65	Op 10 Install Jack Bolts	1.5	34	35.5	142	2130

66	Op 20,30 LO2 Umbilical Align, Mate and Reaction fixture Removal	1.5	35.5	37	148	2220
67	Op 10, 20 LH2 Manifold Press and Jack bolt installation	1.5	34	35.5	142	2130
68	Op 30,40 LH2 Umbilical align, Mate and reaction fixture removal	1.5	35.5	37	148	2220
69	Op 50 LH2 PD 5 I/F Leak Check and Manifold Securing	1	37	38	152	2280
70	V5029.011 LH2 Umbilical and Main Sep Bolt Ordnance Installation	5	38	43	172	2580
71	V5029.012 LO2 Umbilical and Main Sep Bolt Installation	5	38	43	172	2580
72	Op 10,20 Equipment set up and Clear set up	0.5	43	43.5	174	2610
73	OP 30 Stud Pulls	1.5	43.5	45	180	2700
74	Op 40 Ultrasound Inspection	0.5	45	45.5	182	2730
75	Op 50 Clean up and post ops	0.5	45.5	46	184	2760
76	Op 10,20 Equipment set up and Clear set up	0.5	43	43.5	174	2610
77	OP 30 Stud Pulls	1.5	43.5	45	180	2700
78	Op 40 Ultrasound Inspection	0.5	45	45.5	182	2730
79	Op 50 Clean up and post ops	0.5	45.5	46	184	2760
80	V35- 50003 LH2 Flight Strut Installation	3	45	48	192	2880
81	V35- 50010 LO2 Flight Strut Installation	3	46	49	196	2940
82	S0004.445 Op 10 LH Monoball through first inspection	10	48	58	232	3480
83	S0004.450 Op 10 LO2 Monoball through first inspection	10	48	58	232	3480
84	S0004.445 Op 20 LH2 Monoball Part Two, Closeout through Completion	4	58	62	248	3720
85	S0004.450 Op 20 LO2 Monoball Part Two, Closeout through Completion	4	58	62	248	3720
86	V5029.016 UMB Can C/O Outside LO2	3	46	49	196	2940
87	V5029.015 UMB Can C/O Outside LH2	3	46	49	196	2940
88	Op 10 spring and retainer install	1.5	46	47.5	190	2850
89	OP 20 bolt Absorber install	1	46	47	188	2820
90	Op 10 spring and retainer install	1.5	46	47.5	190	2850
91	OP 20 bolt Absorber install	1	46	47	188	2820
92	V35-50004 LO2 Purge Curtain	12	49	61	244	3660
93	V35-50005 LH2 Purge Curtain	12	49	61	244	3660
94	V5170 ET sep Camera install and door closeout	5.5	46	51.5	206	3090
95	OP 10,20,30 Spill Protection thru Mold installation	4	61	65	260	3900
96	Op 40 Foam Application	1.5	61	62.5	250	3750
97	Op 50 Final trim and sell	2	61	63	252	3780
98	Op 60 Fire Barrier	3	61	64	256	3840
99	V5029.013 LH2 Blast Can Close Out Inside	6	46	52	208	3120
100	V5029.014 LO2 Blast Can Close Out Inside	6	46	52	208	3120

101	V5029.021 LH2 Main Sep Bolt Blast Can Close Out Inside	1	46	47	188	2820
102	V5029.020 LO2 Main Sep Bolt Blast Can Close Out Inside	1	46	47	188	2820
103	Preps HUMS Routing	1	71	72	288	4320
104	TP 8 Config	1	65	66	264	3960
105	HUMS Chanelization	10.25	62	72.25	289	4335
106	TP 8 Leak Checks OP 50	1	62	63	252	3780
107	LO2 ET Leak Checks OP 60	3	66.75	69.75	279	4185
108	LH2 ET Leak Checks OP 70	3	62	65	260	3900
109	LO2 T-0 Leak Checks OP 80	2	72.25	74.25	297	4455
110	LH2 T-0 Leak Checks OP 90	2	63.75	65.75	263	3945
111	Flex Hose Bagging OP 30	1	70.5	71.5	286	4290
112	Mass Spec OP 130	12.25	62	74.25	297	4455
113	Gimble measurements	4	65.75	69.75	279	4185
114	Dummy end node	0	74.25	74.25	297	4455

Appendix G: Gantt Chart